GEORGIA INSTITUTE OF TECHNOLOGY — OFFICE OF CONTRACT ADMINISTRATION

PROJECT ADMINISTRATION DATA SHEET

[X] ORIGINAL [ ] REVISION NO. ______

Project No./(Center No.) E-21-607 (R 6241-0A0) GTRC/GIT DATE 12 / 10 / 86

Project Director: A. Rohatgi School/Lab EE

Sponsor: Solar Energy Research Institute (SERI)

Agreement No.: Contract No. XB-7-06070-1 under DE-AC02-83CH10093

Award Period: From 10/1/86 To 9/30/87 (Performance) 9/30/87 Reports

Sponsor Amount:

	New With This Change	Total to Date
Contract Value:	$	$ 53,852
Funded:	$	$ 53,852

Cost Sharing No./(Center No.) ______ Cost Sharing: $ ______

Title: High Efficiency Crystalline Solar Cell Analysis

ADMINISTRATIVE DATA

OCA Contact John B. Schonk

1) Sponsor Technical Contact:

John Benner
Solar Energy Research Institute
1617 Cole Blvd.
Golden, CO 80401-3393

303/231-1396

2) Sponsor Issuing Office:

Margaret A. Lemke
Solar Energy Research Institute
Procurement & Supply Office
1617 Cole Blvd.
Golden, CO 80401-3393
303/231-1858

Military Security Classification: N/A
(or) Company/Industrial Proprietary: N/A

ONR Resident Rep. is ACO: ______ Yes ______ No
Defense Priority Rating: ______

RESTRICTIONS

See Attached Gov't Supplemental Information Sheet for Additional Requirements.

Travel: Foreign travel must have prior approval — Contact OCA in each case. Domestic travel requires sponsor approval where total will exceed greater of $500 or 125% of approved proposal budget category.

Equipment: Title vests with Government

COMMENTS:

SPONSOR'S I.D. NO. 02.240.000.86.007

COPIES TO:

Project Director
Research Administrative Network
Procurement/GTRI Supply Services
Research Security Services
GTRC
Library

GEORGIA INSTITUTE OF TECHNOLOGY OFFICE OF CONTRACT ADMINISTRATION

SPONSORED PROJECT TERMINATION/CLOSEOUT SHEET

Date 4/8/88

Project No. E-21-607 School/~~Lab~~ EE

Includes Subproject No.(s) N/A

Project Director(s) A. Rohatgi GTRC/~~GIT~~

Sponsor Solar Energy Research Institute (SERI)

Title High Efficiency Crystalline Solar Cell Analysis

Effective Completion Date: 9/30/87 (Performance) 9/30/87 (Reports)

Grant/Contract Closeout Actions Remaining:

- [ ] None
- [X] Final Invoice or Copy of Last Invoice Serving as Final
- [X] Release and Assignment
- [X] Final Report of Inventions and/or Subcontract: Patent and Subcontract Questionnaire sent to Project Director [X]
- [X] Govt. Property Inventory & Related Certificate
- [ ] Classified Material Certificate
- [ ] Other

Continues Project No. Continued by Project No.

COPIES TO:

Project Director
Research Administrative Network
Research Property Management
Accounting
Procurement/GTRI Supply Services
Research Security Services
Reports Coordinator (OCA)
Program Administration Division
Contract Support Division

Facilities Management - ERB
Library
GTRC
Project File
Other

E-21-607

BUDGET

I.	DIRECT SALARIES & WAGES	$ 52,885
	A. A. Rohatgi, Associate Professor 4.5 M-Mo. @ $5500/mo.	24,750
	B. C. J. Summers, Principal Research Scientist 1/3 M-Mo. @ $6778/mo.	2,259
	C. Abbas, Research Engineer 1 M-Mo. @ $4276/mo.	4,276
	D. Graduate Research Assistant 6 M-Mo.	12,960
	E. Graduate Research Assistant 4 M-Mo.	8,640
II.	FRINGE BENEFITS @ 21% of direct salaries and wages (less students)	6,570
III.	MATERIALS & SUPPLIES	4,500
IV.	TRAVEL 3 trips to SERI, Denver, CO @ $700/trip and 2 trips to Spire Corp., Boston, MA @ $700/trip	3,500
V.	TOTAL DIRECT COSTS	$ 67,455
VI.	OVERHEAD (indirect costs) @ 63.5%	42,834
VII.	CAPITAL OUTLAY	2,000
III.	TOTAL COSTS	$112,289

1e indirect rates shown are for the period 7/1/85 - 6/30/86 and
ıbject to change.

FORM DOE 536 (1/78)

CONTRACT MANAGEMENT SUMMARY REPORT

FORM APPROVED OMB NO. 38R–0190

1. Contract Identification: High Efficiency Crystalline Solar Cell Analysis

2. Reporting Period: 10/1/86 through 12/30/86

3. Contract Number: XB-7-06070-1

4. Contractor (Name and Address): Solar Energy Research Institute, 1617 Cole Blvd., Golden, CO 80401-3393

5. Contract Start Date: 10/1/86

6. Contract Completion Date: 9/30/87

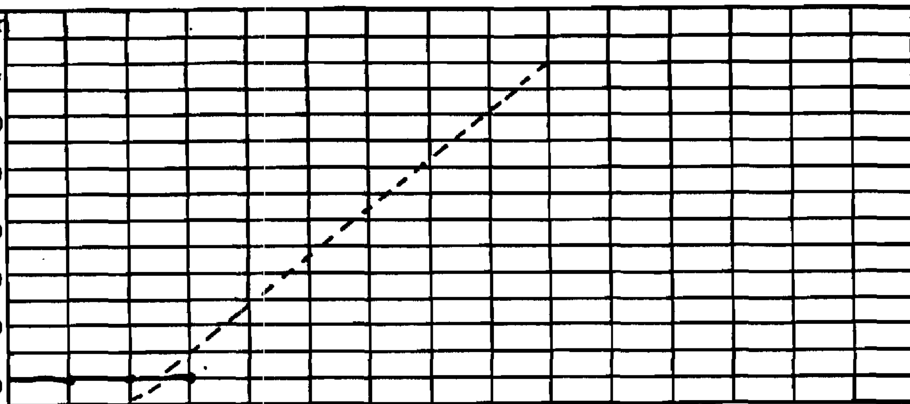
7. Months: O N D J F M A M J J A S

8. FY

9. Cost Status

a. Dollars in Thousands

b. B&R Numbers



Accrued Costs	O	N	D	J	F	M	A	M	J	J	A	S
c. Planned	0	0	7.7	7.7	7.7	7.7	7.7	7.7	7.7	0	0	0
d. Actual	0	0	0									
e. Variance	0	0	0									
f. Cum. Variance	0	0	7.7									

g. Cost Plan Date: 10-1-86

h. Planned Costs Prior FYs: 0

i. Actual Costs Prior FYs: 0

j. Total Estimated Costs for Contract: 53,852

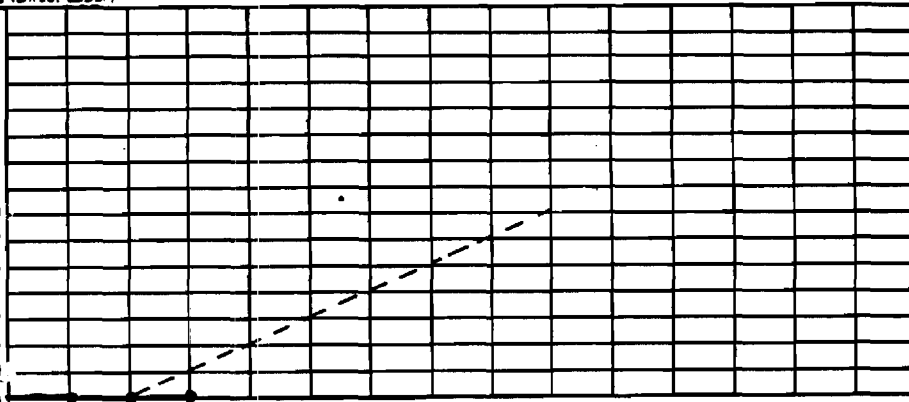
k. Total Contract Value: 53,852

l. Unfilled Orders Outstanding: 1889.50

m. Estimate for Subsequent Reporting Period: 8,975

10. Manpower Status (Direct Labor)

a. Man Hours



Manpower	O	N	D	J	F	M	A	M	J	J	A	S
b. Planned	0	0	197	197	197	197	197	197	197	0	0	0
c. Actual	0	0	0									
d. Variance	0	0	197									

e. Manpower Plan Date: 10-1-86

f. Planned Manpower Prior FYs: 0

g. Actual Manpower Prior FYs: 0

h. Total Estimated Manpower for Contract: 1378

i. Total Contract Manpower: 1378

11. Major Milestone Status

Mod. & Des. — a. Task 1

Coor. Act. — b. Task 2

Mat. Char. — c. Task 3

1 Anal. & Proc. — d. Task 4

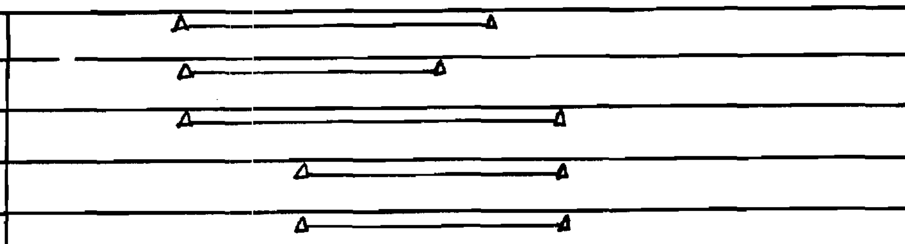
III-V Charact. — e. Task 5

f.

g.

h.

i.



12. Remarks

13. Signature of Contractor's Project Manager and Date: ERohatgi

14. Signature of Government Technical Representative and Date

E-21-?01

GEORGIA INSTITUTE OF TECHNOLOGY
SCHOOL OF ELECTRICAL ENGINEERING
ATLANTA, GEORGIA 30332

LEPHONE: (404) 894-7337

February 16, 1987

Mr. John Benner
Solar Energy Research Institute
1617 Cole Blvd.
Golden, CO 80401-3393

Re: Contract No. XB-7-06070-1 Under DE-AC02-83CH10093

Dear Mr. Benner:

Enclosed please find copies of the Monthly Contract Management Report from 1/1/87-1/31/87.

If you have any questions, please feel free to contact me.

Sincerely yours,

Pam Majors
Administrative Assistant

pm
Enclosures

FORM DOE 536 (1/78)

CONTRACT MANAGEMENT SUMMARY REPORT

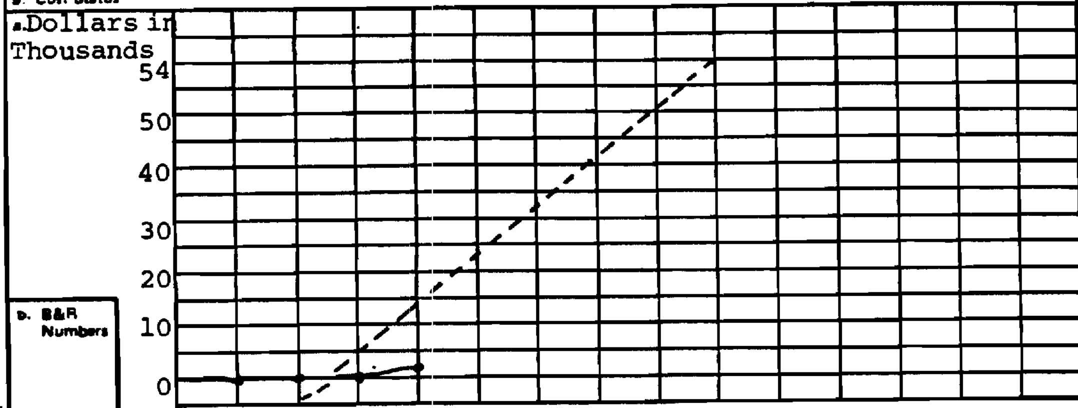
FORM APPROVED OMB NO. 38R–0190

1. Contract Identification: High Efficiency Crystalline Solar Cell Analysis	2. Reporting Period: 1-1-87 through 1-31-87	3. Contract Number: XB-7-06070-1
4. Contractor (Name and Address): Solar Energy Research Institute, 1617 Cole Blvd., Golden, CO 80401-3393	5. Contract Start Date: 10/1/86	6. Contract Completion Date: 9/30/87

7. Months: O N D J F M A M J J A S — 8. FY

9. Cost Status

a. Dollars in Thousands



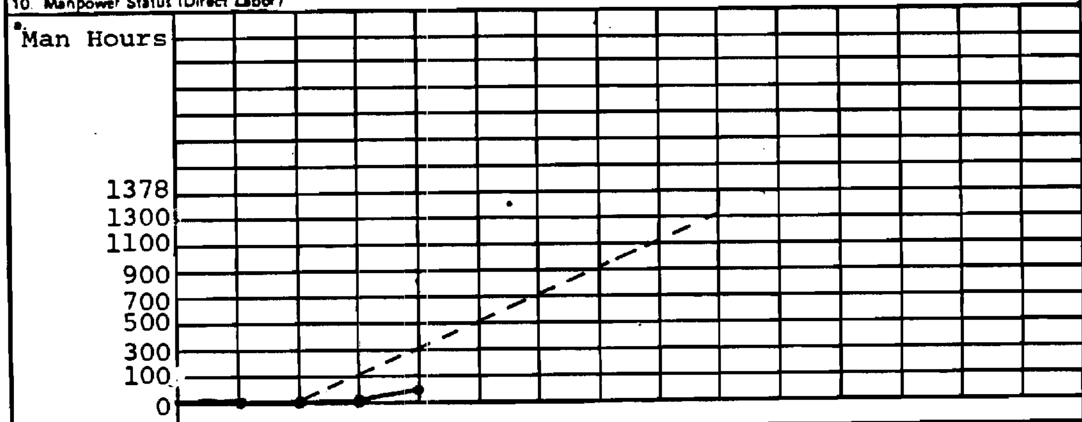
b. B&R Numbers

Accrued Costs	O	N	D	J	F	M	A	M	J	J	A	S
c. Planned	0	0	7.7	7.7	7.7	7.7	7.7	7.7	7.7	0	0	0
d. Actual	0	0	0	1.1								
e. Variance	0	0	0	6.6								
f. Cum. Variance	0	0	7.7	14.3								

g. Cost Plan Date: 10-1-86
h. Planned Costs Prior FYs: 0
i. Actual Costs Prior FYs: 0
j. Total Estimated Costs for Contract: 53,852
k. Total Contract Value: 53,852
l. Unfilled Orders Outstanding: 6794.50
m. Estimate for Subsequent Reporting Period: 8,975

10. Manpower Status (Direct Labor)

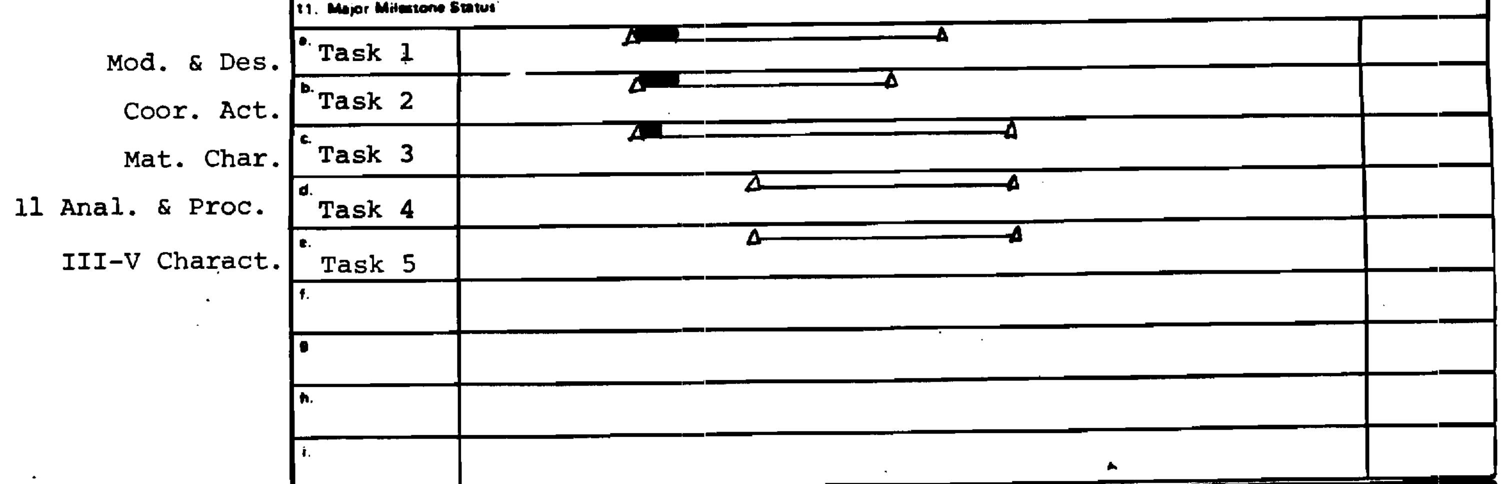
a. Man Hours



Manpower	O	N	D	J	F	M	A	M	J	J	A	S
b. Planned	0	0	197	197	197	197	197	197	197	0	0	0
c. Actual	0	0	0	50								
d. Variance	0	0	197	147								

e. Manpower Plan Date: 10-1-86
f. Planned Manpower Prior FYs: 0
g. Actual Manpower Prior FYs: 0
h. Total Estimated Manpower for Contract: 1378
i. Total Contract Manpower: 1378

11. Major Milestone Status



12. Remarks

13. Signature of Contractor's Project Manager and Date: A Rohatgi

14. Signature of Government Technical Representative and Date

E-21-607

GEORGIA INSTITUTE OF TECHNOLOGY
SCHOOL OF ELECTRICAL ENGINEERING
ATLANTA, GEORGIA 30332

LEPHONE: (404) 894- 7337

March 13, 1987

Ms. Margaret Lemke
Solar Energy Research Institute
1617 Cole Blvd.
Golden, CO 80401-3393

SUBJECT: Contract No. XB-7-06070-1 under DE-AC02-83CH10093
Project Director - A. Rohatgi

Dear Ms. Lemke:

Enclosed please find copies of the Monthly Contract Management Report from 2/1/87-2/28/87.

If you have any questions, please feel free to contact me.

Sincerely yours,

Pam Majors
Administrative Assistant

pm
Enclosures

cc: Mr. John Benner

FORM DOE 536 (1/78)

CONTRACT MANAGEMENT SUMMARY REPORT

FORM APPROVED OMB NO. 38R-0190

1. Contract Identification: High Efficiency Crystalline Solar Cell Analysis

2. Reporting Period: 2-1-87 through 2-28-87

3. Contract Number: XB-7-06070-1

4. Contractor (Name and Address): Solar Energy Research Institute, 1617 Cole Blvd., Golden, CO 80401-3393

5. Contract Start Date: 10/1/86

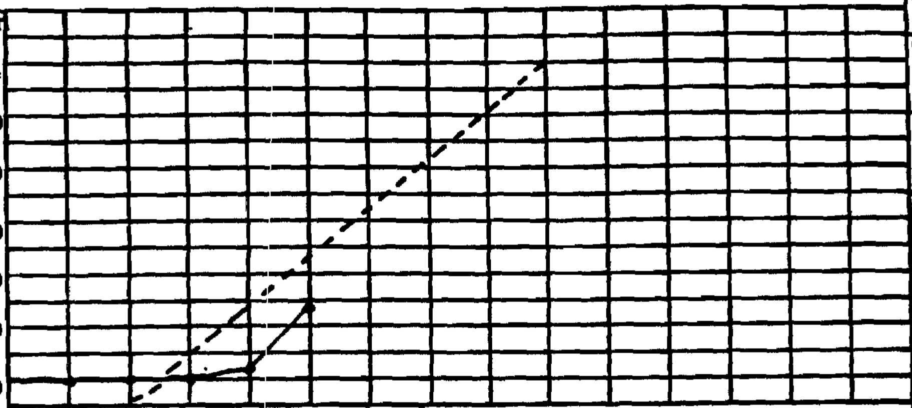
6. Contract Completion Date: 9/30/87

7. Months: O N D J F M A M J J A S

8. FY

9. Cost Status

a. Dollars in Thousands



b. B&R Numbers

Accrued Costs	O	N	D	J	F	M	A	M	J	J	A	S
c. Planned	0	0	7.7	7.7	7.7	7.7	7.7	7.7	7.7	0	0	0
d. Actual	0	0	0	1.1	13.1							
e. Variance	0	0	0	6.6	(5.4)							
f. Cum. Variance	0	0	7.7	14.3	8.9							

g. Cost Plan Date: 10-1-86

h. Planned Costs Prior FYs: 0

i. Actual Costs Prior FYs: 0

j. Total Estimated Costs for Contract: 53,852

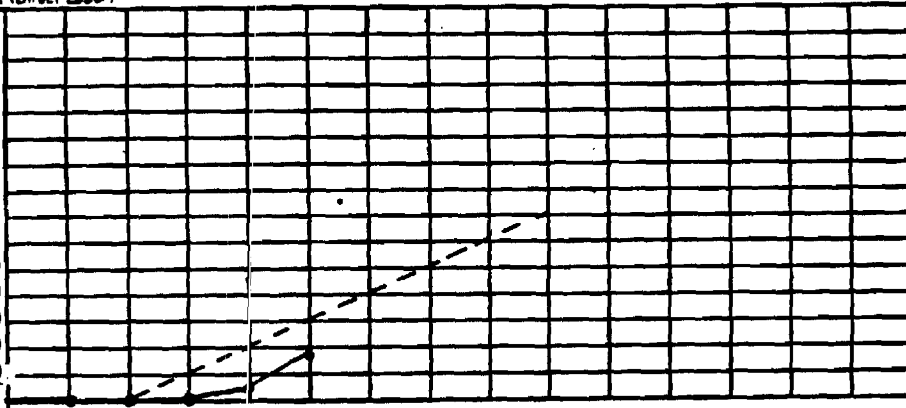
k. Total Contract Value: 53,852

l. Unfilled Orders Outstanding: 1,809

m. Estimate for Subsequent Reporting Period: 9,434

10. Manpower Status (Direct Labor)

a. Man Hours



Manpower	O	N	D	J	F	M	A	M	J	J	A	S
b. Planned	0	0	197	197	197	197	197	197	197	0	0	0
c. Actual	0	0	0	50	195							
d. Variance	0	0	197	147	2							

e. Manpower Plan Date: 10-1-86

f. Planned Manpower Prior FYs: 0

g. Actual Manpower Prior FYs: 0

h. Total Estimated Manpower for Contract: 1378

i. Total Contract Manpower: 1378

11. Major Milestone Status

Mod. & Des. — a. Task 1

Coor. Act. — b. Task 2

Mat. Char. — c. Task 3

ell Anal. & Proc. — d. Task 4

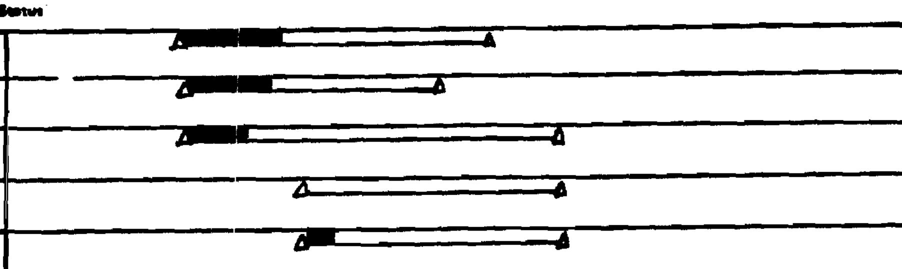
III-V Charact. — e. Task 5

f.

g.

h.

i.



12. Remarks

13. Signature of Contractor's Project Manager and Date: Rohatgi

14. Signature of Government Technical Representative and Date

E-21-607

GEORGIA INSTITUTE OF TECHNOLOGY
SCHOOL OF ELECTRICAL ENGINEERING
ATLANTA, GEORGIA 30332

.EPHONE: (404) 894-7337

April 16, 1987

Ms. Margaret Lemke
Solar Energy Research Institute
1617 Cole Blvd.
Golden, CO 80401-3393

SUBJECT: Contract No. XB-7-06070-1 under DE-AC02-83CH10093
Project Director - A. Rohatgi

Dear Ms. Lemke:

Enclosed please find copies of the Monthly Contract Management Report for the period 3/1/87-3/31/87.

If you have any questions, please feel free to contact me.

Sincerely yours,

Pam Majors
Administrative Assistant

pm
Enclosures

cc: Mr. John Benner

FORM DOE 533
(1/78)

U.S. DEPARTMENT OF ENERGY

CONTRACT MANAGEMENT SUMMARY REPORT

FORM APPROVED
OMB NO. 38R–0190

1. Contract Identification: High Efficiency Crystalline Solar Cell Analysis

2. Reporting Period: ______ through ______

3. Contract Number: XB-7-06070-1

4. Contractor (Name and Address): Solar Energy Research Institute, 1617 Cole Blvd., Golden, CO 80401-3393

5. Contract Start Date: 10/1/86

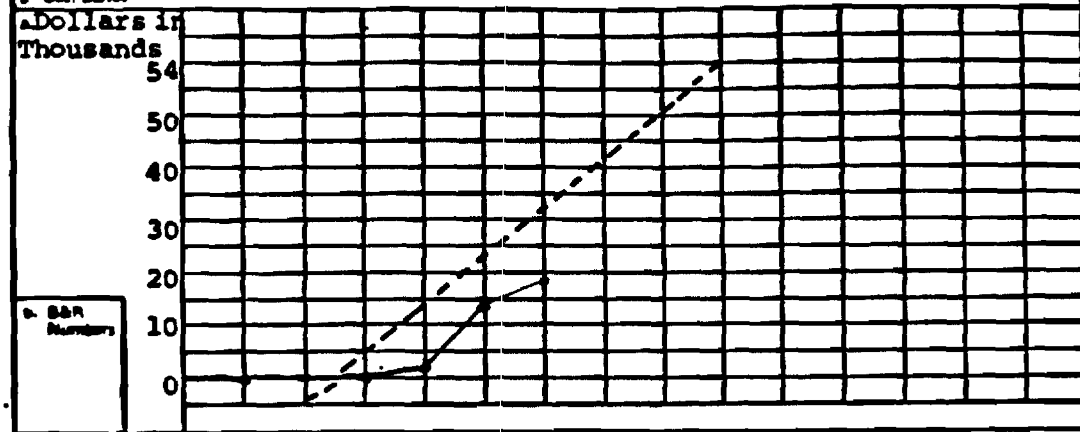
6. Contract Completion Date: 9/30/87

7. Months: O N D J F M A M J J A S

8. FY

9. Cost Status

a. Dollars in Thousands



b. B&R Numbers

Accrued Costs	O	N	D	J	F	M	A	M	J	J	A	S
c. Planned	0	0	7.7	7.7	7.7	7.7	7.7	7.7	7.7	0	0	0
d. Actual	0	0	0	1.1	13.1	2.9						
e. Variance	0	0	0	6.6	(5.4)	4.8						
f. Cum. Variance	0	0	7.7	14.3	8.9	13.7						

g. Cost Plan Date: 10-1-86

h. Planned Costs Prior FYs: 0

i. Actual Costs Prior FYs: 0

j. Total Estimated Costs for Contract: 53,852

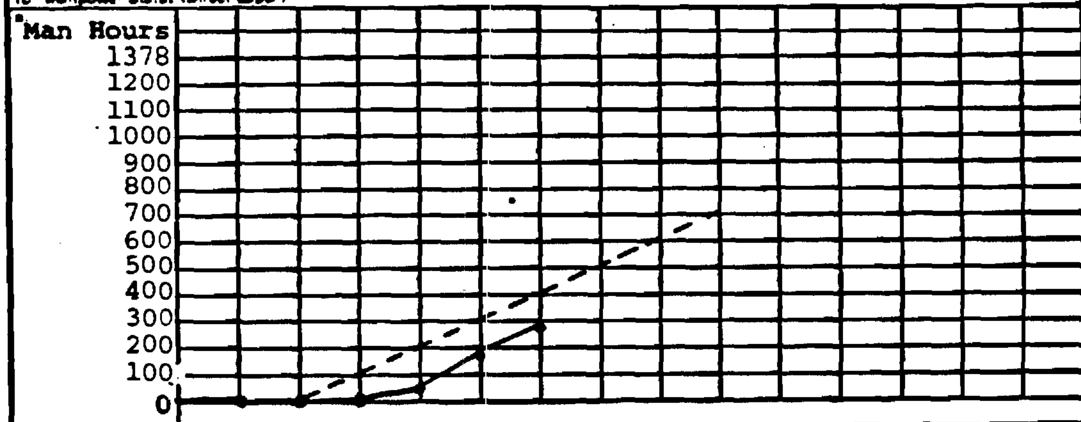
k. Total Contract Value: 53,852

l. Unfilled Orders Outstanding: 4,827

m. Estimate for Subsequent Reporting Period: 10,606

10. Manpower Status (Direct Labor)

a. Man Hours



Manpower	O	N	D	J	F	M	A	M	J	J	A	S
b. Planned	0	0	197	197	197	197	197	197	197	0	0	0
c. Actual	0	0	0	50	195	37.5						
d. Variance	0	0	197	147	2	159.5						

e. Manpower Plan Date: 10-1-86

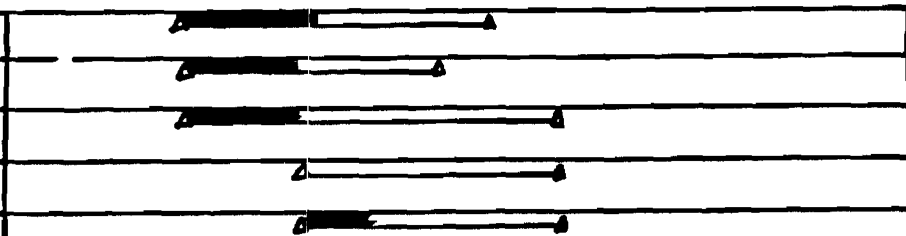
f. Planned Manpower Prior FYs: 0

g. Actual Manpower Prior FYs: 0

h. Total Estimated Manpower for Contract: 1378

i. Total Contract Manpower: 1378

11. Major Milestone Status



Mod. & Des.	a. Task 1
Coor. Act.	b. Task 2
Mat. Char.	c. Task 3
[ana]l. & Proc.	d. Task 4
[II]I-V Charact.	e. Task 5
	f.
	g.
	h.
	i.

12. Remarks

13. Signature of Contractor's Project Manager and Date: Rohatgi

14. Signature of Government Technical Representative and Date

GEORGIA INSTITUTE OF TECHNOLOGY
SCHOOL OF ELECTRICAL ENGINEERING
ATLANTA, GEORGIA 30332

.EPHONE: (404) 894-7337

May 18, 1987

Ms. Margaret Lemke
Solar Energy Research Institute
1617 Cole Blvd.
Golden, CO 80401-3393

SUBJECT: Contract No. XB-7-06070-1 under DE-AC02-83CH10093
Project Director: A. Rohatgi

Dear Ms. Lemke:

Enclosed please find copies of the Monthly Contract Management Report for the period 4/1/87-4/30/87.

If you have any questions, please feel free to contact me.

Sincerely yours,

Pam Majors
Administrative Assistant

pm
Enclosures

cc: Mr. John Benner

U.S. DEPARTMENT OF ENERGY

FORM DOE 533 (8/78)

CONTRACT MANAGEMENT SUMMARY REPORT

FORM APPROVED OMB NO. 38R-0190

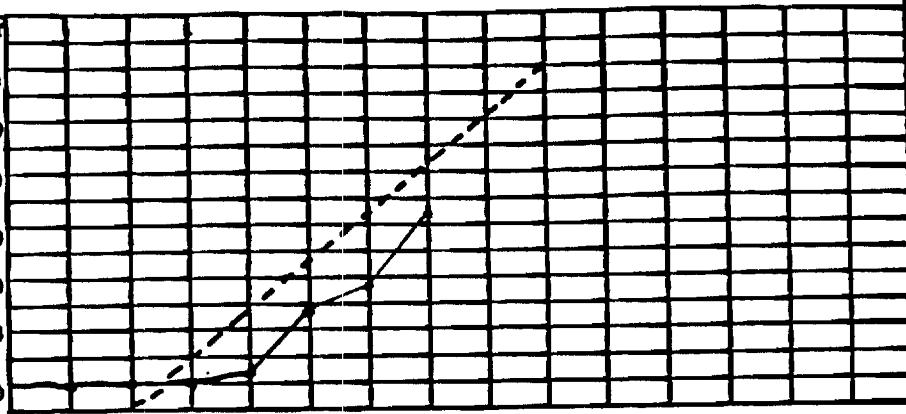
1. Contract Identification: High Efficiency Crystalline Solar Cell Analysis	2. Reporting Period: 4-1-87 through 4-30-87	3. Contract Number: XB-7-06070-1
4. Contractor (Name and Address): Solar Energy Research Institute, 1617 Cole Blvd., Golden, CO 80401-3393		5. Contract Start Date: 10/1/86
		6. Contract Completion Date: 9/30/87

7. Months: O N D J F M A M J J A S

8. FY

9. Cost Status

a. Dollars in Thousands



b. B&R Numbers

Accrued Costs	O	N	D	J	F	M	A	M	J	J	A	S
c. Planned	0	0	7.7	7.7	7.7	7.7	7.7	7.7	7.7	0	0	0
d. Actual	0	0	0	1.1	13.1	2.9	15.6					
e. Variance	0	0	0	6.6	(5.4)	4.8	(7.9)					
f. Cum. Variance	0	0	7.7	14.3	8.9	13.7	5.8					

g. Cost Plan Date: 10-1-86

h. Planned Costs Prior FYs: 0

i. Actual Costs Prior FYs: 0

j. Total Estimated Costs for Contract: 53,852

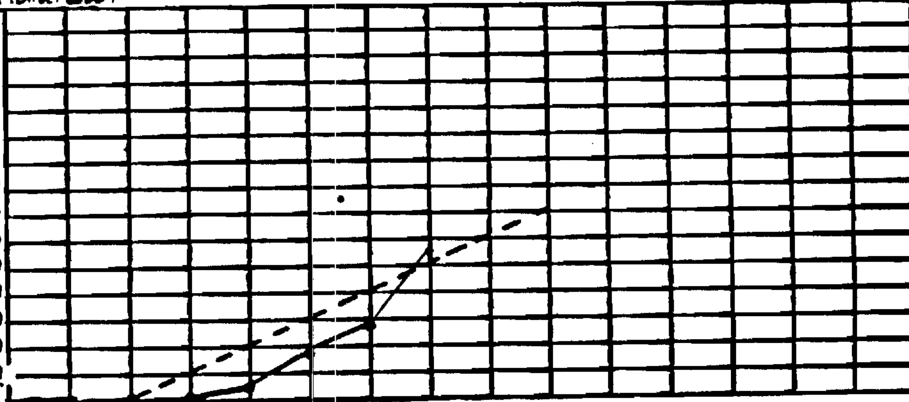
k. Total Contract Value: 53,852

l. Unfilled Orders Outstanding: 14,277

m. Estimate for Subsequent Reporting Period: 3,382

10. Manpower Status (Direct Labor)

a. Man Hours



Manpower	O	N	D	J	F	M	A	M	J	J	A	S
b. Planned	0	0	197	197	197	197	197	197	197	0	0	0
c. Actual	0	0	0	50	195	37.5	263					
d. Variance	0	0	197	147	2	159.5	(66)					

e. Manpower Plan Date: 10-1-86

f. Planned Manpower Prior FYs: 0

g. Actual Manpower Prior FYs: 0

h. Total Estimated Manpower for Contract: 1378

i. Total Contract Manpower: 1378

11. Major Milestone Status

Mod. & Des. a. Task 1

Coor. Act. b. Task 2

Mat. Char. c. Task 3

1. & Proc. d. Task 4

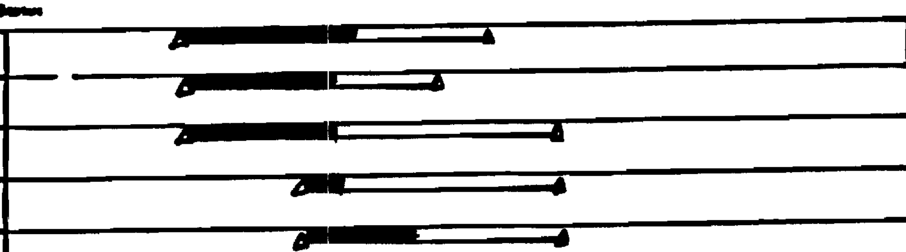
-V Charact. e. Task 5

f.

g.

h.

i.



12. Remarks

13. Signature of Contractor's Project Manager and Date: ERohatgi

14. Signature of Government Technical Representative and Date

GEORGIA INSTITUTE OF TECHNOLOGY
SCHOOL OF ELECTRICAL ENGINEERING
ATLANTA, GEORGIA 30332

.EPHONE: (404) 894- 7337

June 16, 1987

Ms. Margaret Lemke
Solar Energy Research Institute
1617 Cole Blvd.
Golden, CO 80401-3393

SUBJECT: Contract No. XB-7-06070-1 under DE-AC02-83CH10093
Project Director: A. Rohatgi

Dear Ms. Lemke:

Enclosed please find copies of the Monthly Contract Management Report for the period 5/1/87-5/31/87.

If you have any questions, please feel free to contact me.

Sincerely yours,

Pam Majors
Administrative Assistant

pm
Enclosures

cc: Mr. John Benner

U.S. DEPARTMENT OF ENERGY

FORM DOE 535 (1/78)

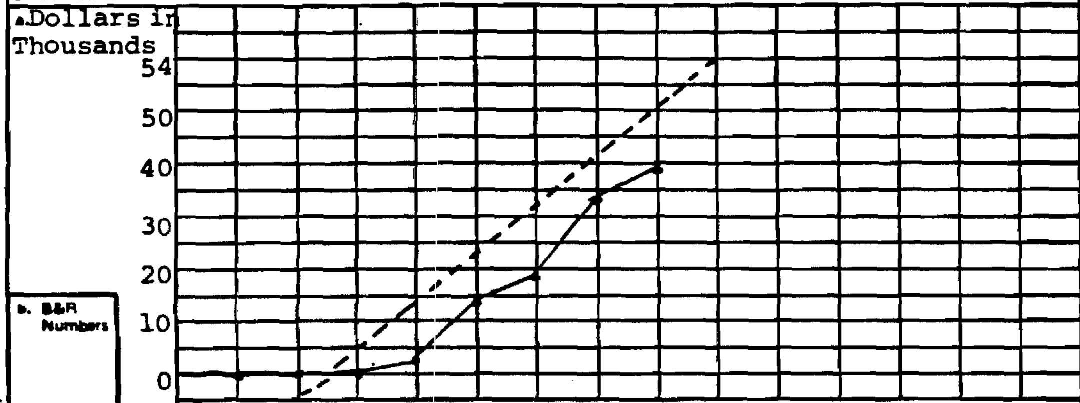
CONTRACT MANAGEMENT SUMMARY REPORT

FORM APPROVED OMB NO. 38R-0190

1. Contract Identification: High Efficiency Crystalline Solar Cell Analysis	2. Reporting Period: 5-1-87 through 5-31-87	3. Contract Number: XB-7-06070-1
4. Contractor (Name and Address): Solar Energy Research Institute, 1617 Cole Blvd., Golden, CO 80401-3393		5. Contract Start Date: 10/1/86
		6. Contract Completion Date: 9/30/87

7. Months: O N D J F M A M J J A S — 8. FY

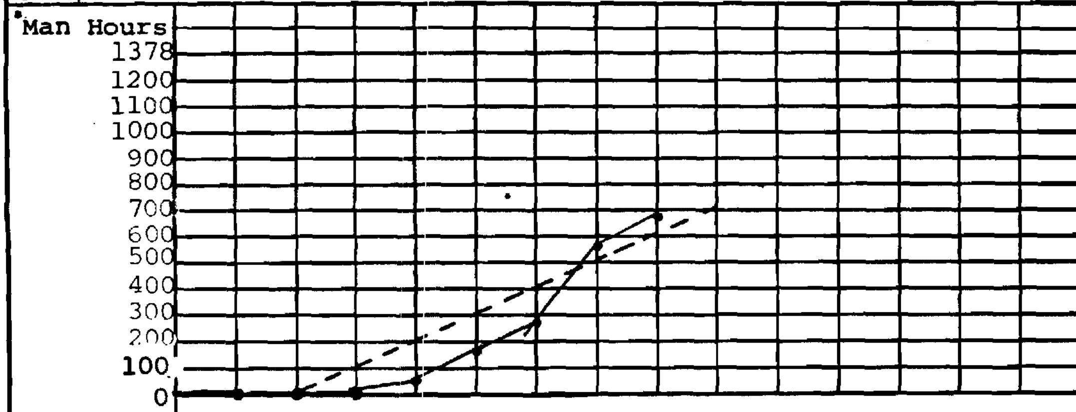
9. Cost Status



Accrued Costs	O	N	D	J	F	M	A	M	J	J	A	S
c. Planned	0	0	7.7	7.7	7.7	7.7	7.7	7.7	7.7	0	0	0
d. Actual	0	0	0	1.1	13.1	2.9	15.6	7.1				
e. Variance	0	0	0	6.6	(5.4)	4.8	(7.9)	.6				
f. Cum. Variance	0	0	7.7	14.3	8.9	13.7	5.8	6.4				

g. Cost Plan Date: 10-1-86
h. Planned Costs Prior FYs: 0
i. Actual Costs Prior FYs: 0
j. Total Estimated Costs for Contract: 53,852
k. Total Contract Value: 53,852
l. Unfilled Orders Outstanding: 7,139
m. Estimate for Subsequent Reporting Period: 6,764

10. Manpower Status (Direct Labor)

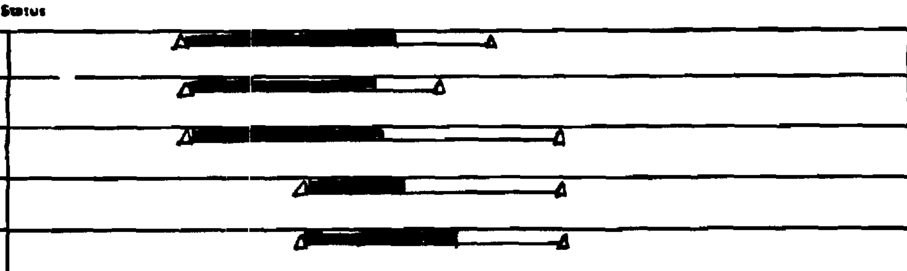


Manpower	O	N	D	J	F	M	A	M	J	J	A	S
b. Planned	0	0	197	197	197	197	197	197	197	0	0	0
c. Actual	0	0	0	50	195	37.5	263	151				
d. Variance	0	0	197	147	2	159.5	(66)	46				

e. Manpower Plan Date: 10-1-86
f. Planned Manpower Prior FYs: 0
g. Actual Manpower Prior FYs: 0
h. Total Estimated Manpower for Contract: 1378
i. Total Contract Manpower: 1378

11. Major Milestone Status

Mod. & Des. — a. Task 1
Coor. Act. — b. Task 2
Mat. Char. — c. Task 3
1 Anal. & Proc. — d. Task 4
III-V Charact. — e. Task 5
f.
g.
h.
i.



12. Remarks

13. Signature of Contractor's Project Manager and Date: Rohatgi

14. Signature of Government Technical Representative and Date

GEORGIA INSTITUTE OF TECHNOLOGY
SCHOOL OF ELECTRICAL ENGINEERING
ATLANTA, GEORGIA 30332

EPHONE: (404) 894- 7337

July 24, 1987

Ms. Margaret Lemke
Solar Energy Research Institute
1617 Cole Blvd.
Golden, CO 80401-3393

SUBJECT: Contract No. XB-7-06070-1 Under DE-AC02-83CH10093
Project Director: A. Rohatgi

Dear Ms. Lemke:

Enclosed please find copies of the Monthly Contract Management Report for the period 6/1/87-6/30/87.

If you have any questions, please feel free to contact me.

Sincerely yours,

Pam Majors
Administrative Assistant

pm
Enclosures

cc: Mr. John Benner

U.S. DEPARTMENT OF ENERGY

FORM DOE 536 (1/78)

CONTRACT MANAGEMENT SUMMARY REPORT

FORM APPROVED OMB NO. 38R-0190

1. Contract Identification: High Efficiency Crystalline Solar Cell Analysis

2. Reporting Period: 6/1/87 through 6/30/87

3. Contract Number: XB-7-06070-1

4. Contractor (Name and Address): Solar Energy Research Institute, 1617 Cole Blvd., Golden, CO 80401-3393

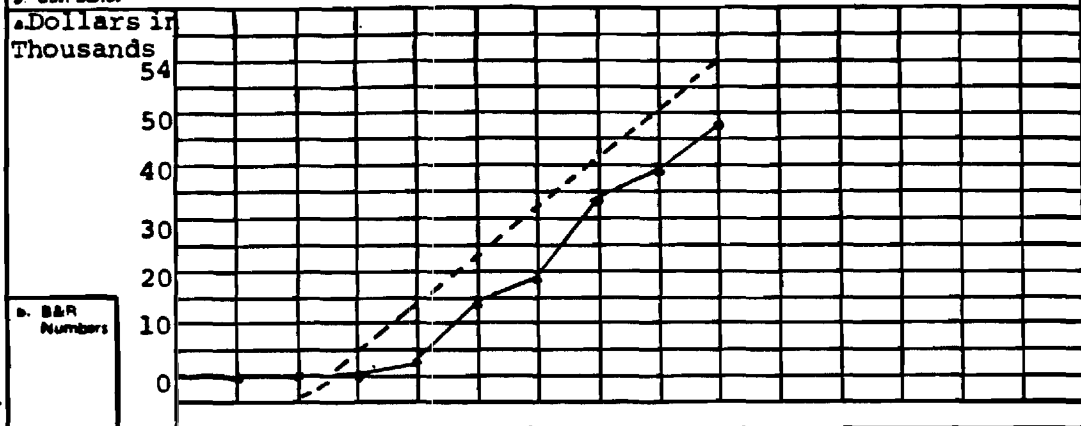
5. Contract Start Date: 10/1/86

6. Contract Completion Date: 9/30/87

7. Months: O N D J F M A M J J A S

8. FY

9. Cost Status



g. Cost Plan Date: 10-1-86

h. Planned Costs Prior FYs: 0

i. Actual Costs Prior FYs: 0

j. Total Estimated Costs for Contract: 53,852

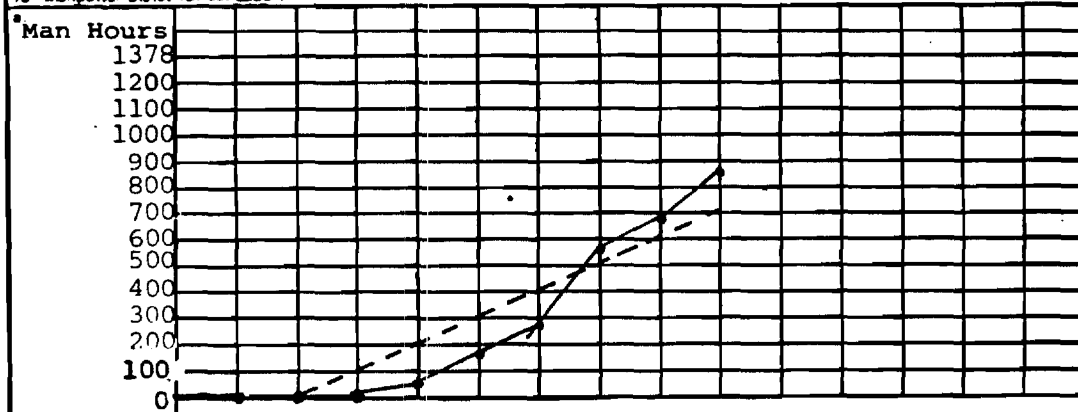
k. Total Contract Value: 53,852

l. Unfilled Orders Outstanding

m. Estimate for Subsequent Reporting Period

Accrued Costs	O	N	D	J	F	M	A	M	J	J	A	S
c. Planned	0	0	7.7	7.7	7.7	7.7	7.7	7.7	7.7	0	0	0
d. Actual	0	0	0	1.1	13.1	2.9	15.6	7.1	7.1			
e. Variance	0	0	0	6.6	(5.4)	4.8	(7.9)	.6	.6			
f. Cum. Variance	0	0	7.7	14.3	8.9	13.7	5.8	6.4	7.0			

10. Manpower Status (Direct Labor)



e. Manpower Plan Date: 10-1-86

f. Planned Manpower Prior FYs: 0

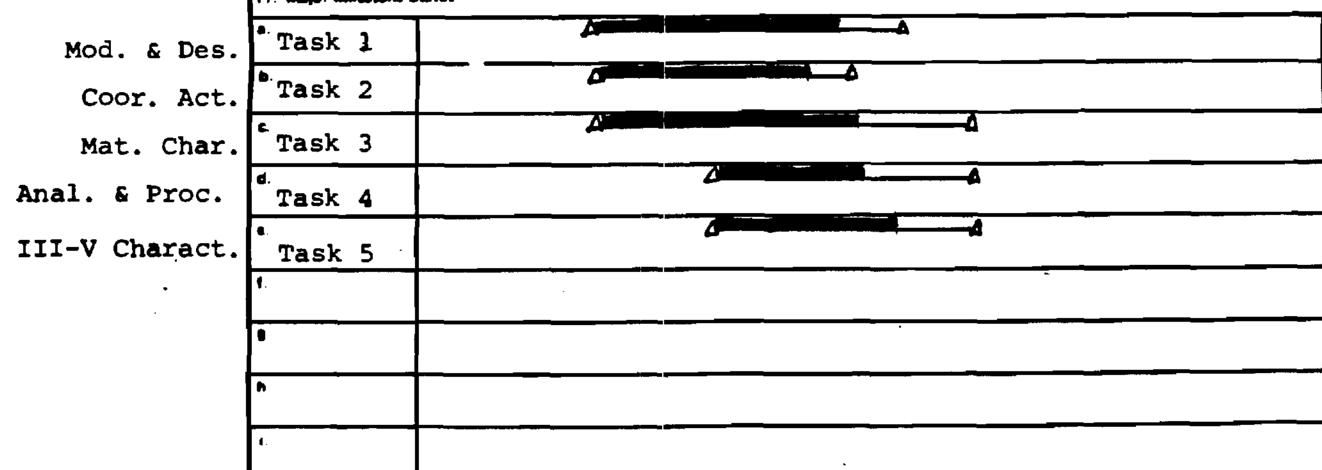
g. Actual Manpower Prior FYs: 0

h. Total Estimated Manpower for Contract: 1378

i. Total Contract Manpower: 1378

Manpower	O	N	D	J	F	M	A	M	J	J	A	S
b. Planned	0	0	197	197	197	197	197	197	197	0	0	0
c. Actual	0	0	0	50	195	37.5	263	151	151			
d. Variance	0	0	197	147	2	159.5	(66)	46	46			

11. Major Milestone Status



12. Remarks

13. Signature of Contractor's Project Manager and Date: Rohatgi

14. Signature of Government Technical Representative and Date

GEORGIA INSTITUTE OF TECHNOLOGY
SCHOOL OF ELECTRICAL ENGINEERING
ATLANTA, GEORGIA 30332

.EPHONE: (404) 894-7337

August 17, 1987

Ms. Margaret Lemke
Solar Energy Research Institute
1617 Cole Blvd.
Golden, CO 80401-3393

SUBJECT: Contract No. XB-7-06070-1 under DE-AC02-83CH10093
Project Director: A. Rohatgi

Dear Ms. Lemke:

Enclosed please find copies of the Monthly Contract Management Report for the period 7/1/87-7/31/87 on the above referenced contract.

If you have any questions, please feel free to contact me.

Sincerely yours,

Pam Majors
Administrative Assistant

pm
Enclosures

cc: Mr. John Benner

U.S. DEPARTMENT OF ENERGY

FORM DOE 535 (1/78)

CONTRACT MANAGEMENT SUMMARY REPORT

FORM APPROVED OMB NO. 38R-0190

1. Contract Identification: High Efficiency Crystalline Solar Cell Analysis

2. Reporting Period: 7/1/87 through 7/31/87

3. Contract Number: XB-7-06070-1

4. Contractor (Name and Address): Solar Energy Research Institute, 1617 Cole Blvd., Golden, CO 80401-3393

5. Contract Start Date: 10/1/86

6. Contract Completion Date: 9/30/87

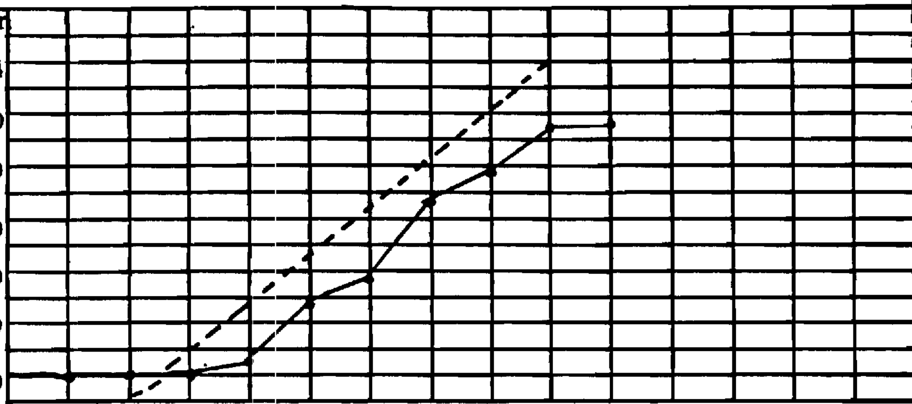
7. Months: O N D J F M A M J J A S

8. FY

9. Cost Status

a. Dollars in Thousands

54
50
40
30
20
10
0



b. B&R Numbers

Accrued Costs	O	N	D	J	F	M	A	M	J	J	A	S			
c. Planned	0	0	7.7	7.7	7.7	7.7	7.7	7.7	7.7	0	0	0			
d. Actual	0	0	0	1.1	13.1	2.9	15.6	7.1	7.1	.3					
e. Variance	0	0	0	6.6	(5.4)	4.8	(7.9)	.6	.6	(.3)					
f. Cum. Variance	0	0	7.7	14.3	8.9	13.7	5.8	6.4	7.0	4.0					

g. Cost Plan Date: 10-1-86

h. Planned Costs Prior FYs: 0

i. Actual Costs Prior FYs: 0

j. Total Estimated Costs for Contract: 53,852

k. Total Contract Value: 53,852

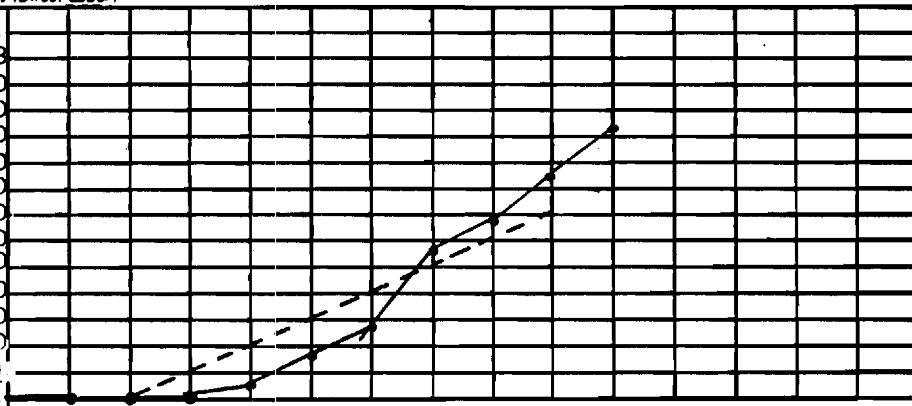
l. Unfilled Orders Outstanding: 7,466

m. Estimate for Subsequent Reporting Period: 7,466

10. Manpower Status (Direct Labor)

a. Man Hours

1378
1200
1100
1000
900
800
700
600
500
400
300
200
100
0



Manpower	O	N	D	J	F	M	A	M	J	J	A	S			
b. Planned	0	0	197	197	197	197	197	197	197	0	0	0			
c. Actual	0	0	0	50	195	37.5	263	151	151	20					
d. Variance	0	0	197	147	2	159.5	(66)	46	46	(20)					

e. Manpower Plan Date: 10-1-86

f. Planned Manpower Prior FY's: 0

g. Actual Manpower Prior FY's: 0

h. Total Estimated Manpower for Contract: 1378

i. Total Contract Manpower: 1378

11. Major Milestone Status

Mod. & Des. — a. Task 1

Coor. Act. — b. Task 2

Mat. Char. — c. Task 3

Anal. & Proc. — d. Task 4

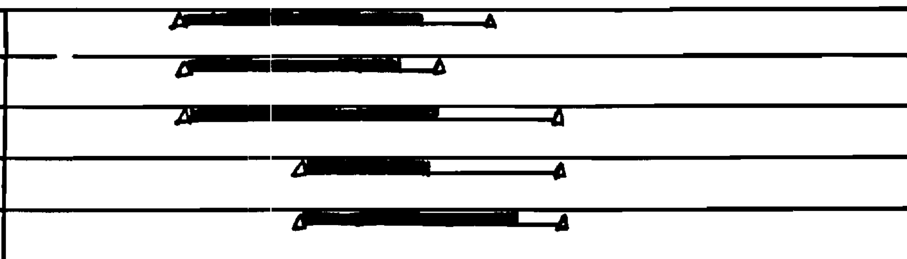
III-V Charact. — e. Task 5

f.

g.

h.

i.



12. Remarks

13. Signature of Contractor's Project Manager and Date: Rohatgi

14. Signature of Government Technical Representative and Date

GEORGIA INSTITUTE OF TECHNOLOGY
SCHOOL OF ELECTRICAL ENGINEERING
ATLANTA, GEORGIA 30332

EPHONE: (404) 894-7337

September 16, 1987

Ms. Margaret Lemke
Solar Energy Research Institute
1617 Cole Blvd.
Golden, CO 80401-3393

SUBJECT: Contract No. XB-7-06070-1 under DE-AC02-83CH10093
Project Director: A. Rohatgi

Dear Ms. Lemke:

Enclosed please find copies of the Monthly Contract Management Report for the period 8/1/87-8/31/87 on the above referenced contract.

If you have any questions, please feel free to contact me.

Sincerely yours,

Pam Majors
Administrative Assistant

pm
Enclosures

cc: Mr. John Benner

U.S. DEPARTMENT OF ENERGY

FORM DOE 536 (1/78)

CONTRACT MANAGEMENT SUMMARY REPORT

FORM APPROVED OMB NO. 38R–0190

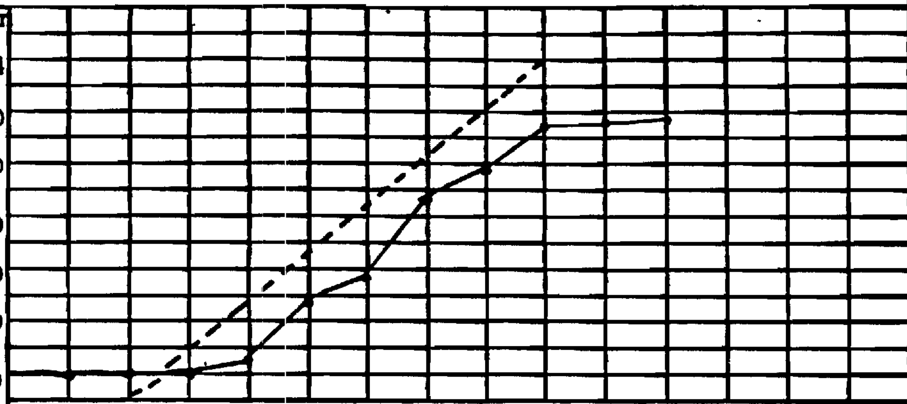
1. Contract Identification: High Efficiency Crystalline Solar Cell Analysis	2. Reporting Period: 8/1/87 through 8/31/87	3. Contract Number: XB-7-06070-1
4. Contractor (Name and Address): Solar Energy Research Institute, 1617 Cole Blvd., Golden, CO 80401-3393		5. Contract Start Date: 10/1/86
		6. Contract Completion Date: 9/30/87

7. Months: O N D J F M A M J J A S — 8. FY

9. Cost Status

a. Dollars in Thousands (0, 10, 20, 30, 40, 50, 54)

b. B&R Numbers



9.		O	N	D	J	F	M	A	M	J	J	A	S
Accrued Costs	c. Planned	0	0	7.7	7.7	7.7	7.7	7.7	7.7	7.7	0	0	0
	d. Actual	0	0	0	1.1	13.1	2.9	15.6	7.1	7.1	.3	.3	
	e. Variance	0	0	0	6.6	(5.4)	4.8	(7.9)	.6	.6	(.3)	(.3)	
	f. Cum Variance	0	0	7.7	14.3	8.9	13.7	5.8	6.4	7.0	4.0	.1	

g. Cost Plan Date: 10-1-86

h. Planned Costs Prior FYs: 0

i. Actual Costs Prior FYs: 0

j. Total Estimated Costs for Contract: 53,852

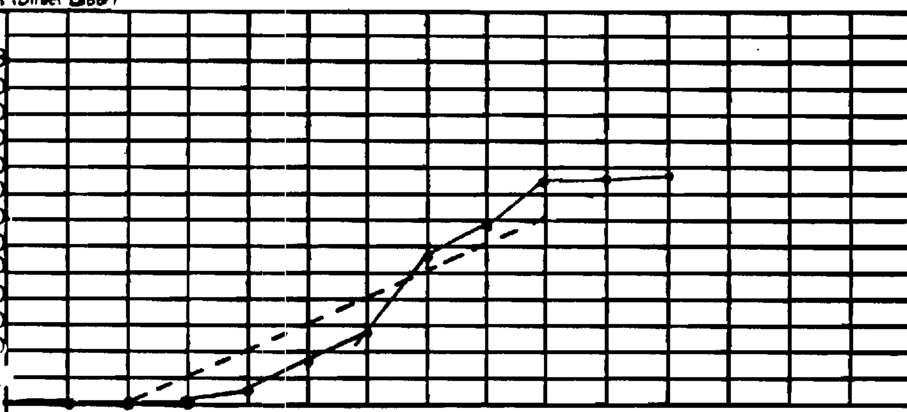
k. Total Contract Value: 53,852

l. Unfilled Orders Outstanding: 5,987

m. Estimate for Subsequent Reporting Period: 5,987

10. Manpower Status (Direct Labor)

a. Man Hours (0, 100, 200, 300, 400, 500, 600, 700, 800, 900, 1000, 1100, 1200, 1378)



10.		O	N	D	J	F	M	A	M	J	J	A	S
Manpower	b. Planned	0	0	197	197	197	197	197	197	197	0	0	0
	c. Actual	0	0	0	50	195	37.5	263	151	151	20	20	
	d. Variance	0	0	197	147	2	159.5	(66)	46	46	(20)	(20)	

e. Manpower Plan Date: 10-1-86

f. Planned Manpower Prior FYs: 0

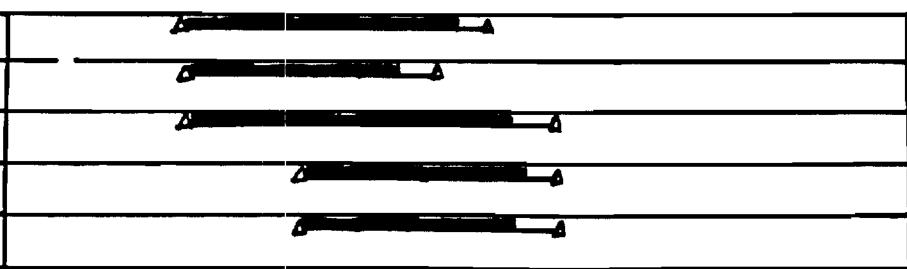
g. Actual Manpower Prior FYs: 0

h. Total Estimated Manpower for Contract: 1378

i. Total Contract Manpower: 1378

11. Major Milestone Status

Mod. & Des.	a. Task 1
Coor. Act.	b. Task 2
Mat. Char.	c. Task 3
Anal. & Proc.	d. Task 4
III-V Charact.	e. Task 5
	f
	g
	h
	i



12. Remarks

13. Signature of Contractor's Project Manager and Date: Rohatgi

14. Signature of Government Technical Representative and Date

GEORGIA INSTITUTE OF TECHNOLOGY
SCHOOL OF ELECTRICAL ENGINEERING
ATLANTA, GEORGIA 30332

.EPHONE: (404) 894-7337

October 15, 1987

Ms. Margaret Lemke
Solar Energy Research Institute
1617 Cole Blvd.
Golden, CO 80401-3393

SUBJECT: Contract No. XB-7-06070-1 under DE-AC02-83CH10093
Project Director: A. Rohatgi

Dear Ms. Lemke:

Enclosed please find copies of the Monthly Contract Management Report for the period 9/1/87-9/30/87 on the above referenced contract. Some orders were placed prior to the termination date of 9/30/87, but expenditures will not appear until next month. We will send a final report then.

If you have any questions, pleae feel free to contact me.

Sincerely,

Pam Majors
Research Administrator

pm
Enclosures

cc: Mr. John Benner

U.S. DEPARTMENT OF ENERGY

FORM DOE 533 (1/78)

CONTRACT MANAGEMENT SUMMARY REPORT

FORM APPROVED OMB NO. 38R–0190

1. Contract Identification: High Efficiency Crystalline Solar Cell Analysis

2. Reporting Period: 9/1/87 through 9/30/87

3. Contract Number: XB-7-06070-1

4. Contractor (Name and Address): Solar Energy Research Institute, 1617 Cole Blvd. Golden, CO 80401-3393

5. Contract Start Date: 10/1/86

6. Contract Completion Date: 9/30/87

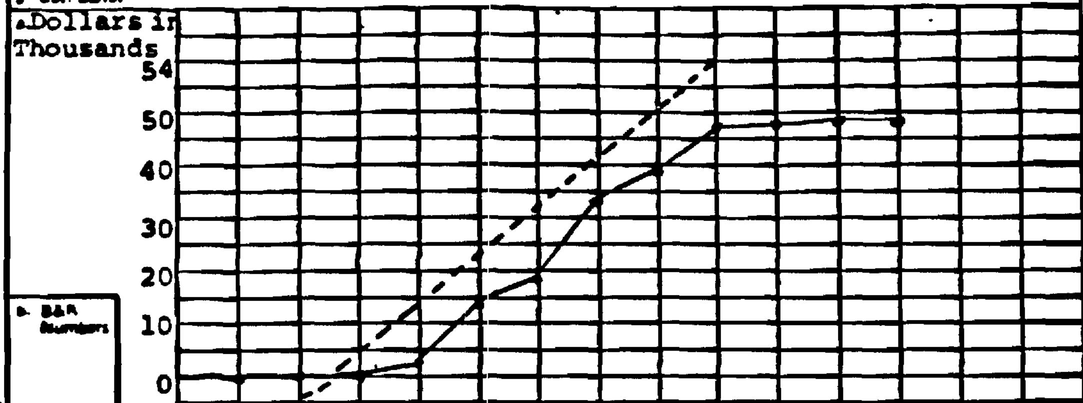
7. Months: O N D J F M A M J J A S

8. FY

9. Cost Status

a. Dollars in Thousands

b. B&R Numbers



g. Cost Plan Date: 10-1-86

h. Planned Costs Prior FYs: 0

i. Actual Costs Prior FYs: 0

j. Total Estimated Costs for Contract: 53,852

k. Total Contract Value: 53,852

l. Unfilled Orders Outstanding: 5,558

m. Estimate for Subsequent Reporting Period: 5,558

Accrued Costs	O	N	D	J	F	M	A	M	J	J	A	S
c. Planned	0	0	7.7	7.7	7.7	7.7	7.7	7.7	7.7	0	0	0
d. Actual	0	0	0	1.1	13.1	2.9	15.6	7.1	7.1	.3	.3	.4
e. Variance	0	0	0	6.6	(5.4)	4.8	(7.9)	.6	.6	(.3)	(.3)	(.4)
f. Cum Variance	0	0	7.7	14.3	8.9	13.7	5.8	6.4	7.0	4.0	.1	(.3)

10. Manpower Status (Direct Labor)

a. Man Hours

e. Manpower Plan Date: 10-1-86

f. Planned Manpower Prior FYs: 0

g. Actual Manpower Prior FYs: 0

h. Total Estimated Manpower for Contract: 1378

i. Total Contract Manpower: 1378

Manpower	O	N	D	J	F	M	A	M	J	J	A	S
b. Planned	0	0	197	197	197	197	197	197	197	0	0	0
c. Actual	0	0	0	50	195	37.5	263	151	151	20	20	20
d. Variance	0	0	197	147	2	159,5	(66)	46	46	(20)	(20)	(20)

11. Major Milestone Status

Mod. & Des.	a. Task 1
Coor. Act.	b. Task 2
Mat. Char.	c. Task 3
al. & Proc.	d. Task 4
I-V Charact.	e. Task 5
	f.
	g.
	h.
	i.

12. Remarks

13. Signature of Contractor's Project Manager and Date: Rohatgi

14. Signature of Government Technical Representative and Date

E-21-601

HIGH EFFICIENCY CRYSTALLINE

SOLAR CELL RESEARCH

A. Rohatgi

First Report for the Period

October 30 to December 31, 1986

Solar Energy Research Institute

Contract No. XB-7-06070-1

GEORGIA INSTITUTE OF TECHNOLOGY
SCHOOL OF ELECTRICAL ENGINEERING
ATLANTA, GEORGIA 30332

Technical Progress

The major objective of this program is to design and analyze high efficiency silicon solar cells. Solar cells will be fabricated at the Spire Corporation, with the goal of achieving $\geq$ 20% efficiency.

This is the first report on this program and it covers the work done up to December 31, 1986. During this period we have obtained a computer to start solar cell modeling. In addition, we also ordered and obtained a solar cell modeling program "PC 1D" from Iowa State University. Paul Alexander and James Gee of Sandia National Lab were quite helpful and supportive of this model. We have also made a few trial runs using PC 1D and it seems to work fine. Arlyn Smith, a Ph.D student in the electrical engineering department, is learning how to run the program and understand the details, strength, and weaknesses of the PC 1D model. We now also have the latest versions (4 and 5) of "SPCOLAY" modeling program, courtesy of Prof. M. Wolf. In addition, we have our own recombination velocity and open circuit voltage models. Arlyn Smith has a strong computer background and interest in solar cells and will look into the modeling aspect of this program.

On December 18, 1986, we had the first meeting with Ted Ciszek of SERI, and Mark Spitzer of Spire Corporation to plan the experimental work in this program. It was decided to start a baseline run, already in progress at Spire Corporation, using the standard 0.3 Ω-cm wacker float zone silicon to assess the starting cell efficiency in this program. These cells will then come to Georgia Tech for the analysis and based on that design and process inputs to Spire Corporation will be provided for the next run.

It was also decided that Ted Ciszek will soon provide us with some of the high lifetime float zone material, which will be first analyzed at Georgia Tech and then sent to Spire Corporation with the design inputs. Ciszek's material is expected to be small in diameter, therefore, we may have to make 1 cm x 1 cm cells.

One of the problems, that is holding down the efficiency of Spire Corporation's cell, is low minority carrier diffusion length (135-200 microns). In order to expedite the research in this regard, we have already obtained some samples from Spire Coporation, from their previous runs, to perform DLTS measurements and detect the centers that are hurting the carrier lifetime in the Spire cells. Some of these samples were actually 2 cm x 2 cm cells, which have now been transformed into small area cells to perform DLTS measurements. Godfrey Augustine, another student in the electrical engineering department will soon start learning and making DLTS measurements on these samples. Our DLTS set-up is fully automated and functional and we expect to report some DLTS results in the next report.

E-21-6??

GEORGIA INSTITUTE OF TECHNOLOGY
SCHOOL OF ELECTRICAL ENGINEERING
ATLANTA, GEORGIA 30332

PHONE: (404) 894-7337

May 5, 1987

Mr. John Benner
Solar Energy Research Institute
1617 Cole Blvd.
Golden, CO 80401-3393

Re: Contract No. XB-7-06070-1 under DE-AC02-83CH10093

Dear Mr. Benner:

Please find attached copies the Quarterly Technical Status Report for the period 1/1/87-3/31/87 on the above referenced project.

If you have any questions, please feel free to contact me.

Sincerely yours,

Pam Majors
Administrative Assistant

pm
Attachments

cc: Margaret Lemke

HIGH EFFICIENCY CRYSTALLINE SOLAR CELL RESEARCH

A. Rohatgi

Second Report for the Period
January 1 to March 30, 1987

Solar Energy Research Institute

Contract No. XB 7-06070-1

GEORGIA INSTITUTE OF TECHNOLOGY
SCHOOL OF ELECTRICAL ENGINEERING
ATLANTA, GEORGIA 30332

Technical Progress

A. Solar Cell Modelling and Design

In this report we describe our progress in the area of solar cell modelling and DLTS analysis to identify the source of low carrier lifetime in float zone cells being processed at SPIRE. We now have both SPCOLAY and PC-1D model on our computer. PC-1D was bought from Iowa University and SPCOLAY was obtained from the University of Pennsylvania, courtesy of M. Wolf. In addition, we have our own model for Voc and the effect of surface recombination velocity.

During this period we made model calculations using SPCOLAY and PC-1D to design greater than 20% efficient cells, using practically achievable material and process parameters. We plan to continue such calculations to find the strength and weakness of each model. Advanced design features like surface passivation, heavy doping effects, reduced cell thickness, and back surface reflector are included in these calculations.

The modeling program PC-1D was run using inputs that were as similar as possible to the input for the program SPCOLAY in an attempt to determine the difference in the two programs. The values in Table 1 show some of the results obtained.

In the program PC-1D all of the donar and acceptor enhancement factors for the SRH lifetimes were set to zero. The SRH lifetime was then changed until the total minority carrier lifetime, which included the SRH along with the auger and the direct lifetimes, was set to a specified value. This made if possible to set the minority carrier lifetime to a value which would give the same diffusion length also used the value of the mobility of the carrier. The mobility of the carriers was found by doing a sample run and reading the value off the plot generated by PC-1D. Samples of the plots for the minority carrier lifetime and diffusion length as a function of distance are included as figures 1 and 2. In addition there are two plots which are blow-ups of the emitter region of the cell seen in figures 3 and 4. All these graphs are for the cell with the back surface reflector.

The last two plots, figures 5 and 6 included show the generation and recombination as a function of distance and the current voltage curve of the solar cell. These are for the 20.8% efficient 150 micron cell with a surface concentration of 1E19 and the back surface reflector added.

Table 1 shows that the interplay between the design features and diffusion length. We find that PC-1D and SPOCLAY agree within 0.5% for the absolute value efficiency. PC-1D generally predicts slightly higher value of Voc and lower value for Jsc compared to SPOCLAY. In these calculations diffusion length was varied in the range of 150-300μm, which is typical for the low resistivity Wacker float zone silicon cells.

According to these model calculations 20.3% cell can be realized with a diffusion length of 300 microns provided cell is thinned down to 150μm. PC-1D model, which can take into account the back surface reflector effect, shows than an efficient BSR can give efficiency as high as 20.8%. Notice that these calculations were done for diffused solar cells with surface concentration as high as 2×10^{20} Cm^{-3}. We are now trying to put Spire's 18-19% efficient cells through the model calculations. We have obtained most of the necessary input data from Spire. Our objective will be to modify the cell design in a clever manner so that without using any unreasonable material and process parameters we can design solar cells with efficiencies approaching 25%.

A. DLTS Measurements and Analysis of Spire Samples

We performed the above model calculations using diffusion length in the range of 150-300μm, which is typical of high efficiency solar cells fabricated to date on low resistivity float zone silicon. Spire cells generally show diffusion length in the range of 150-200μm but the diffused cells fabricated on similar material by Green and Rohatgi have shown diffusion length in the range of 220-300μm. Through DLTS measurements on selected samples we are trying to find out why Spire cells have low diffusion length. Improved diffusion length in Spire cells alone can increase the cell efficiency from 18-19% to 19-20% range.

Table 2 shows a description of samples supplied by Spire along with the measured diffusion length on each sample. Each sample had small dot-size electrode to perform the DLTS measurements. Samples with implanted junctions had ohmic dot contacts so the DLTS measurement can look into the depletion region formed by the ion-implanted junction. Those samples which did not have any junction at the end of processing Ti-Ag Schottky dots were deposited for the DLTS measurements.

Figure 7 shows the output of our automated DLTS system for the sample So, which was ion implanted and then etched with KOH to remove the implanted region. A Ti-Ag Schottky was made for the DLTS. This wafer, which was supposed to be a representative of the as-grown material, showed two large deep levels at E_V + 0.41 eV and E_V + 0.86 eV with trap densities of 1.66 x 10^{14} Cm^{-3} and 2.8 x 10^{13} Cm^{-3} respectively. We believe that ion-implantation + KOH removal introduced these levels and that they are not present in the starting virgin material.

Comparison of the DLTS spectra for samples S1 and S2 (Figure 8) show that S2 has no peaks but S1 has two peaks. S1 was annealed without any preclean + ion implanted + laser annealed while S2 was first cleaned properly + ion implanted + laser annealed. Thus we conclude the furnace anneal without any cleaning is responsible for introducing two deep levels, L_1 and L_2, which in turn reduces the diffusion length to 20 microns.

Sample S3 which was cleaned + furnace annealed + ion implanted + laser annealed showed only the level L_2 and not L_1. Thus a comparison of samples S_3 and S_1 suggest that level L_1 is due to bypassing the precleaning step prior to furnace anneal. Since deep level L_2 is common to both samples S1 and S3, the data indicate that level L_1 is a lifetime killer because of which diffusion length in the sample S1 is only 20 microns compared to 120 microns in sample S3.

Comparison of DLTS spectra for samples S2 and S3 suggests that the L2 level observed in sample S2 is due to the furnace contamination because S3, which never saw the furnace anneal, showed no deep levels. Thus level L2 is also a lifetime killer and its presence decreases the diffusion length in sample S3 to 120 microns compared to 150 microns in S2.

Sample S4 was cleaned + ion implanted + furnace annealed + etched and cleaned + ion implanted + laser annealed. Thus compared to Sample S3 this sample had an additional implant but its diffusion length is only 60 microns. Both S3 and S4 showed the deep level L2 with similar trap density values. At this point, based on surface DLTS measurement, it is difficult to explain why S3 has a diffusion length of 120 microns while S4 has a diffusion length of 60 microns.

Thus our preliminary DLTS measurements on Spire processed material suggest that improper cleaning and furnace contamination can be responsible for reducing the diffusion length in the Spire cells to less than 150 microns. However, implanted and laser annealed cells appear clean with no detectable deep levels and have a diffusion length of $\geq$ 150 microns. It should be recognized that our DLTS detection limit for these 0.3Ω-cm p-type float zone silicon is about 10^{13} Cm^{-3}. More experiments are in progress to understand the lifetime behavior in the Spire-processed material so that higher efficiency cells can be made.

In the next couple of months we will (a) do the analysis of very high quality galluim doped silicon from Ted Ciszek (b) perform model calculations for achieving greater than 20% cells from this material and (c) fabricate and analyze high efficiency cells on this material as well as Wacker FZ, using the Spire process. Cell processing for this program is now in progress at Spire.

Acknowledgement The author would like to acknowledge the assistantce of Arlyn Smith (GRA) who is doing the solar cell modelling and Godfrey Augustine (GRA) who is doing the DLTS measurements and analysis.

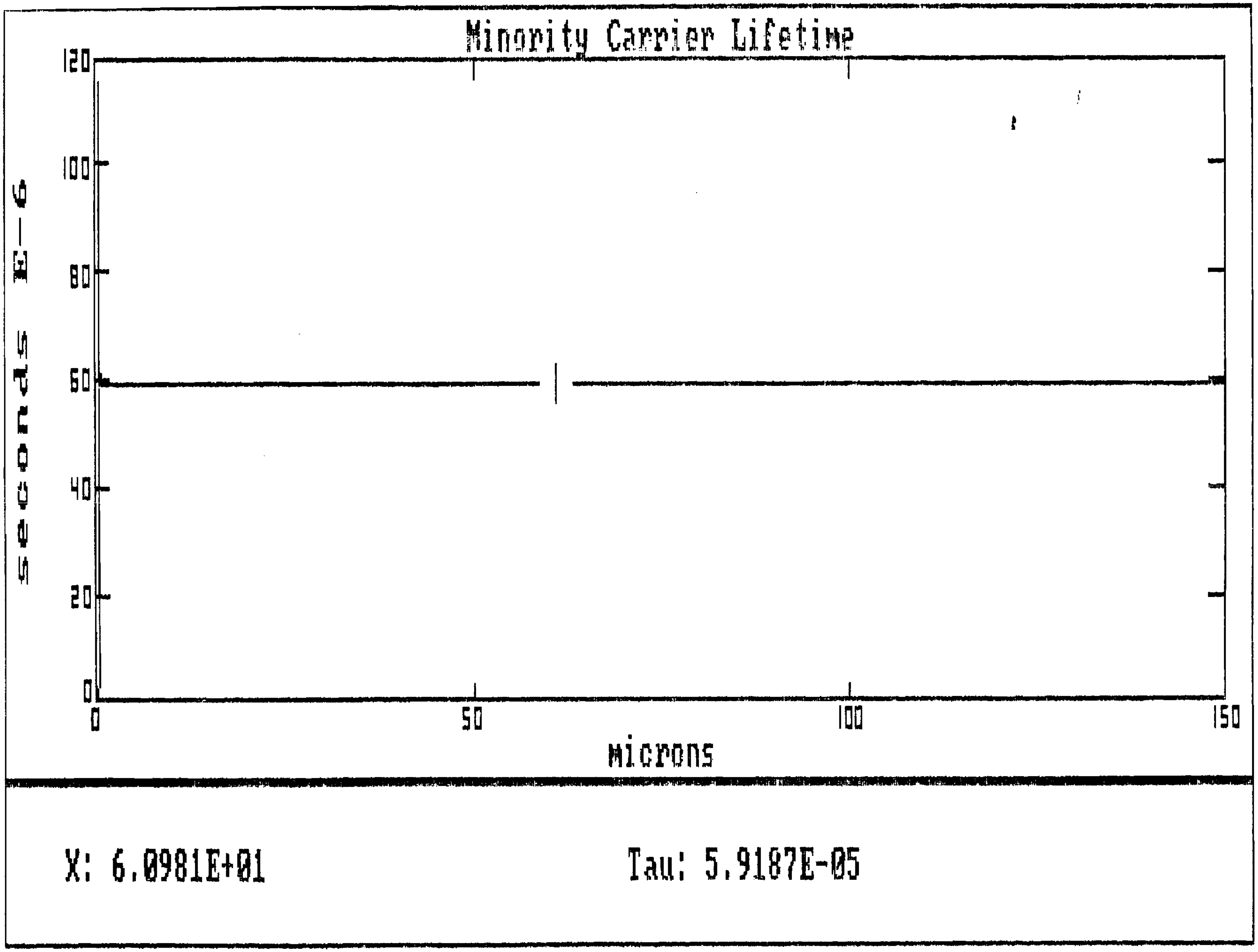

Minority Carrier Lifetime
120
100
80
60
40
20
0
seconds E-6
0
50
100
150
microns
X: 6.0981E+01
Tau: 5.9187E-05

Figure 1

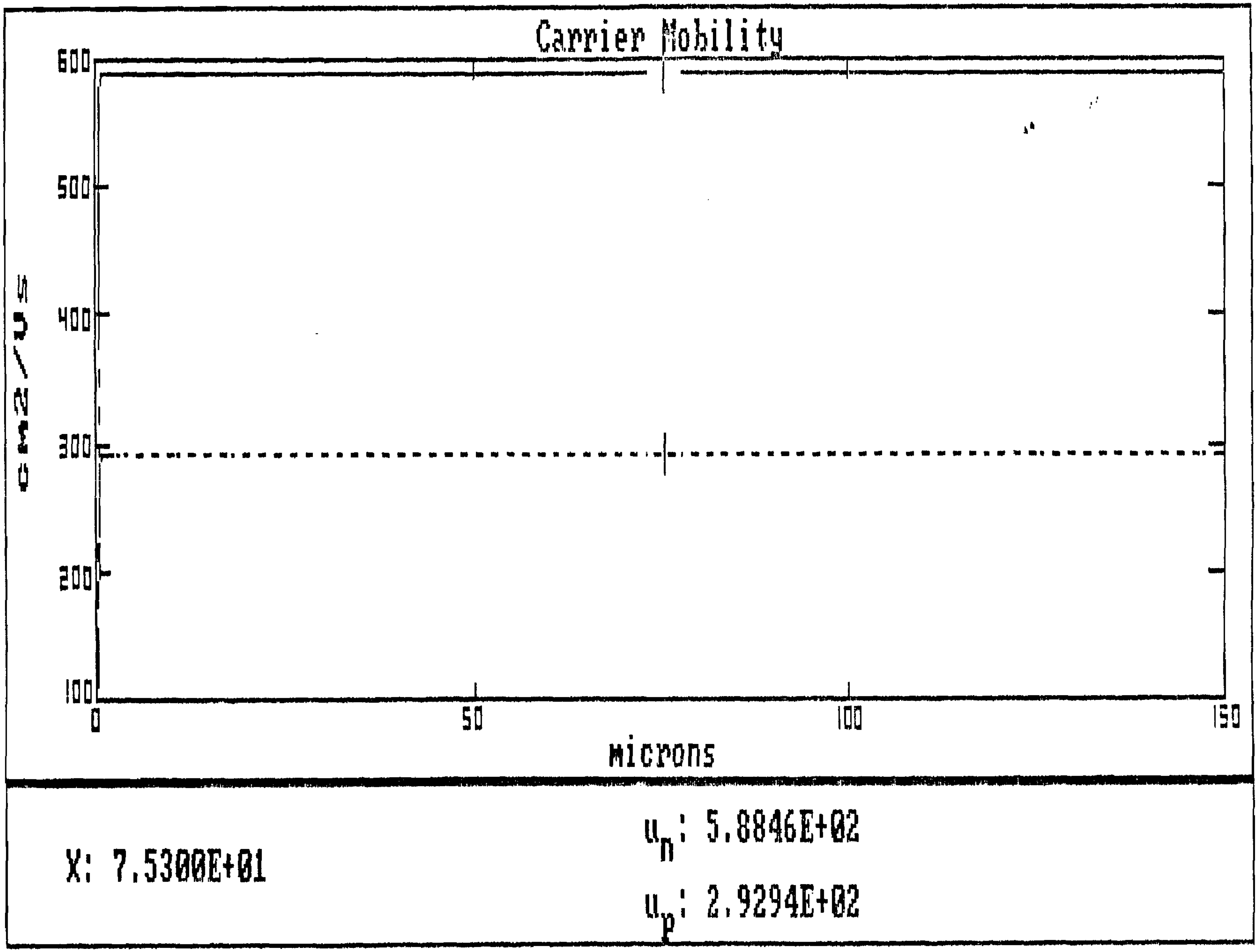

Carrier Mobility
600
500
400
300
200
100
cm2/us
0
50
100
150
microns
X: 7.5300E+01
un: 5.8846E+02
up: 2.9294E+02

Figure 2

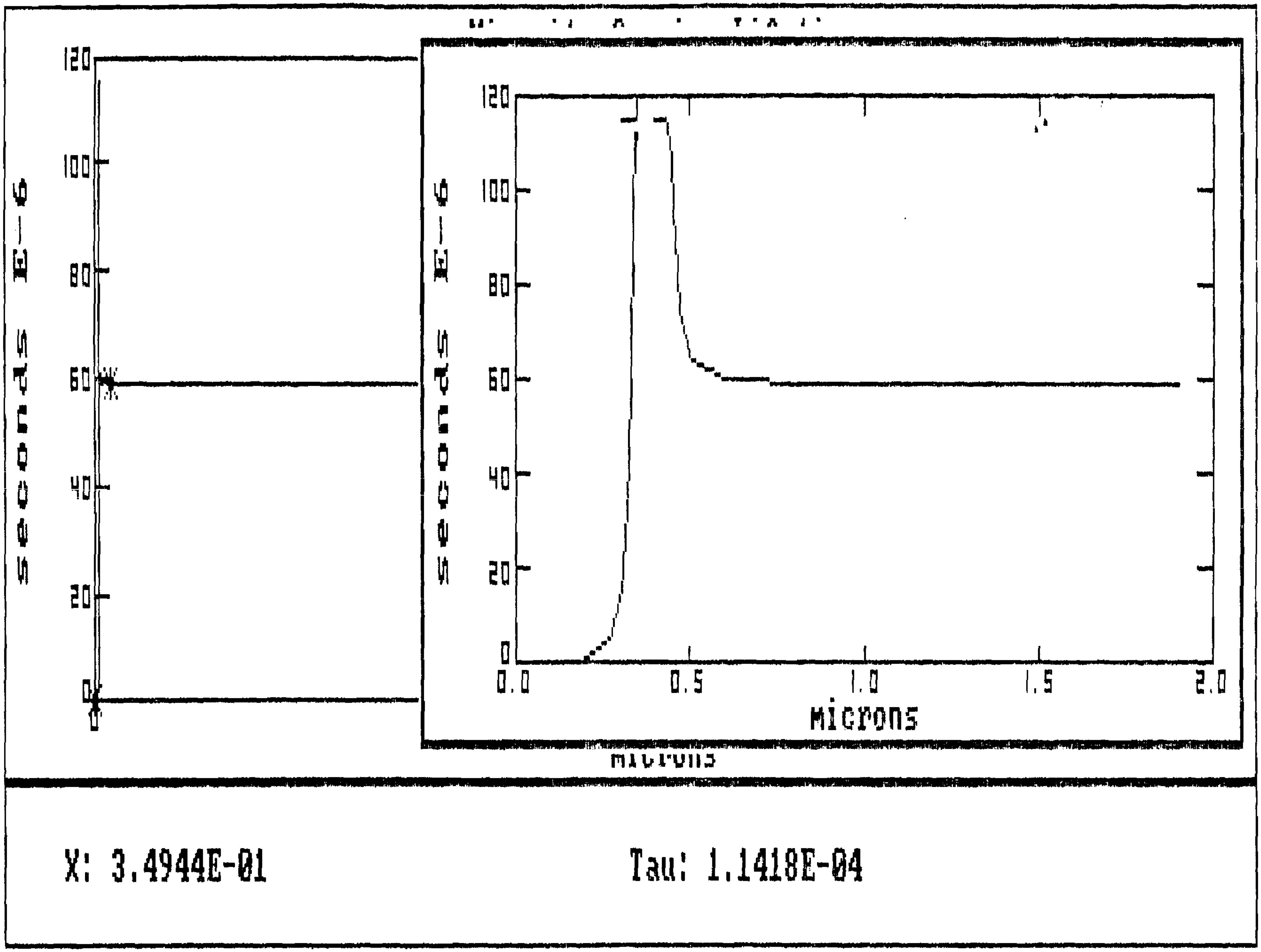

seconds E-6
120
100
80
60
40
20
0
0.0
0.5
1.0
1.5
2.0
microns
X: 3.4944E-01
Tau: 1.1418E-04

Figure 3

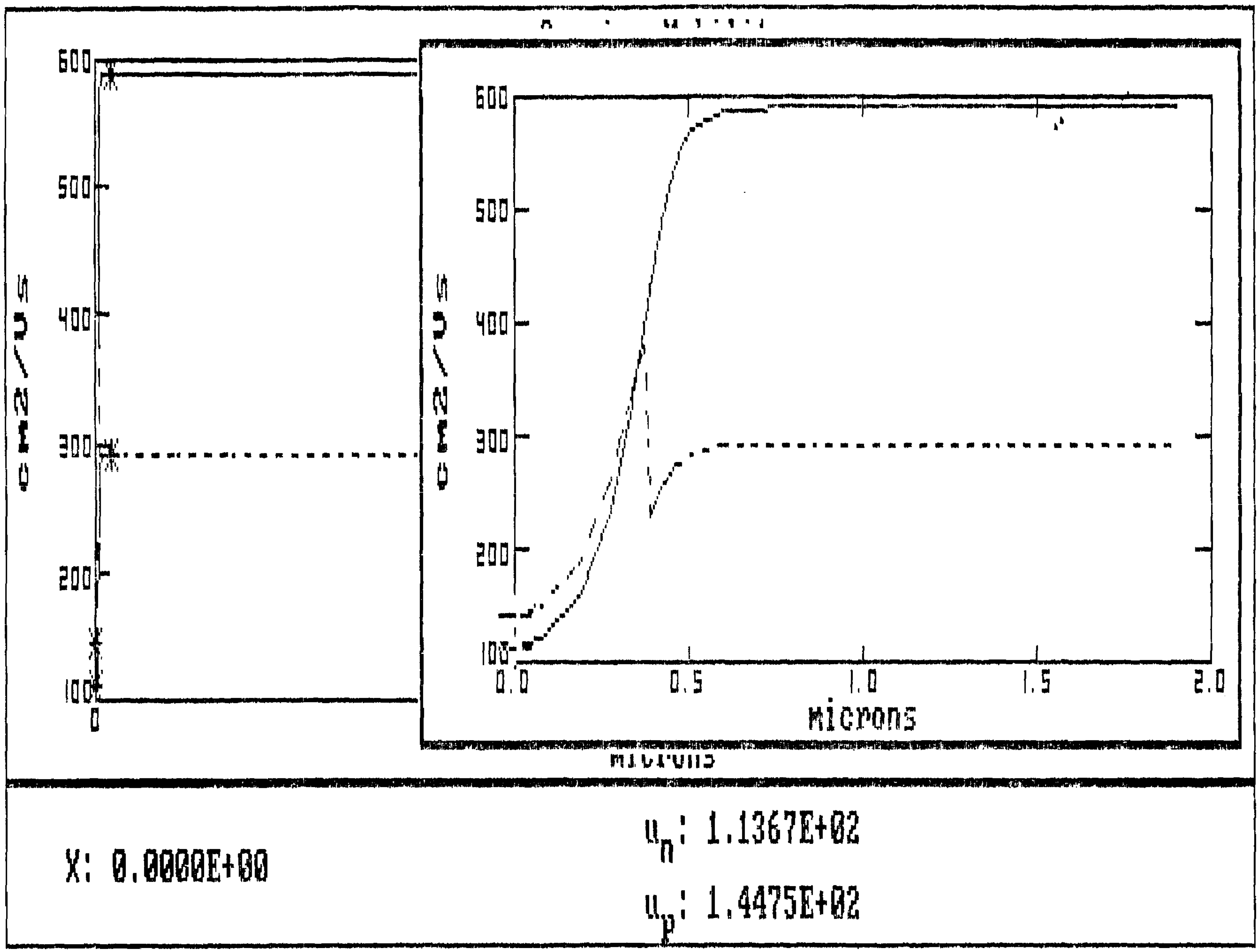

600
500
400
300
200
100
0
cm2/us
600
500
400
300
200
100
0.0
0.5
1.0
1.5
2.0
microns
X: 0.0000E+00
u_n: 1.1367E+02
u_p: 1.4475E+02

Figure 4

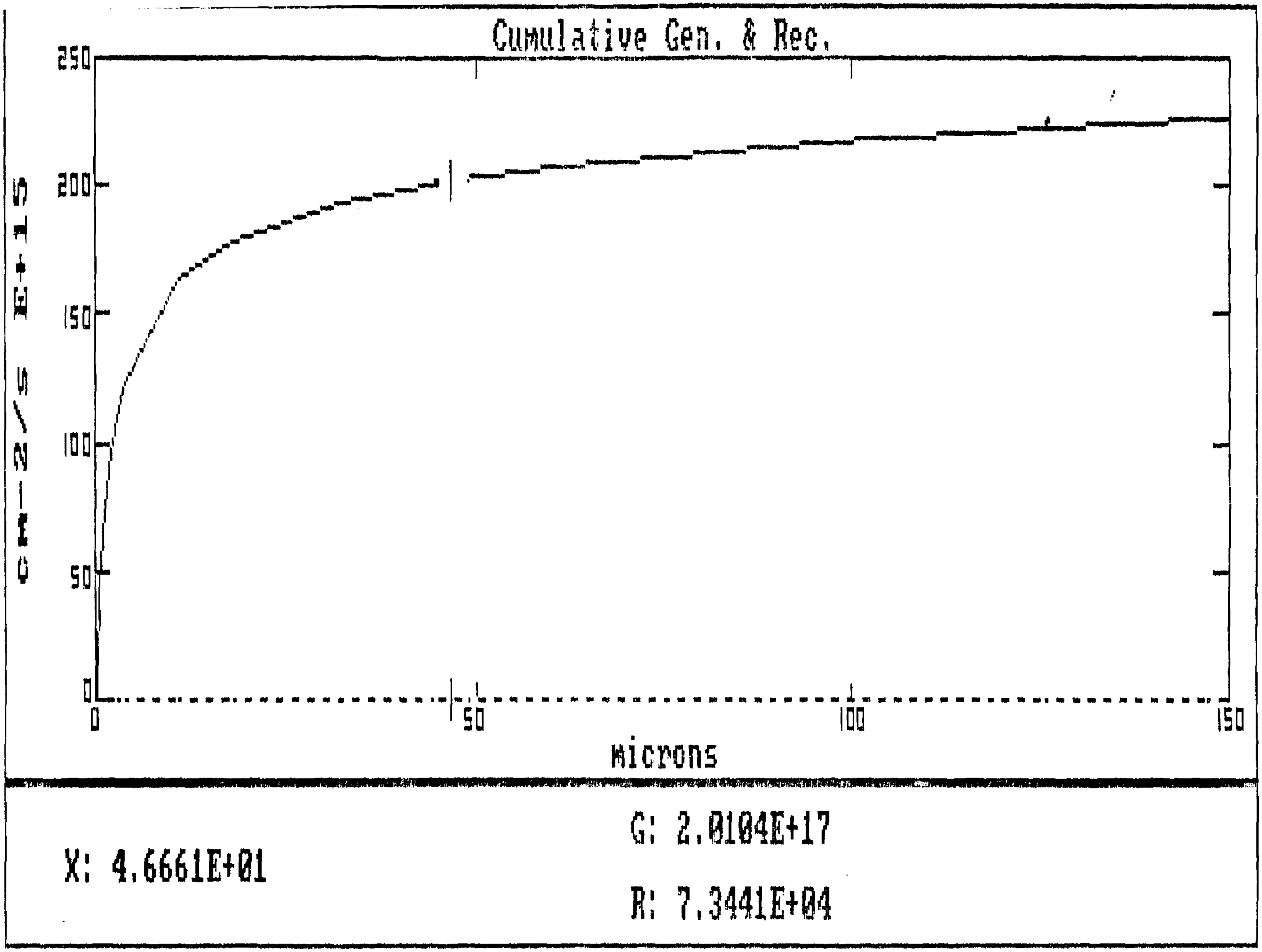

Cumulative Gen. & Rec.
250
200
150
100
50
0
cm-2/s E+15
0
50
100
150
microns
X: 4.6661E+01
G: 2.0104E+17
R: 7.3441E+04

Figure 5

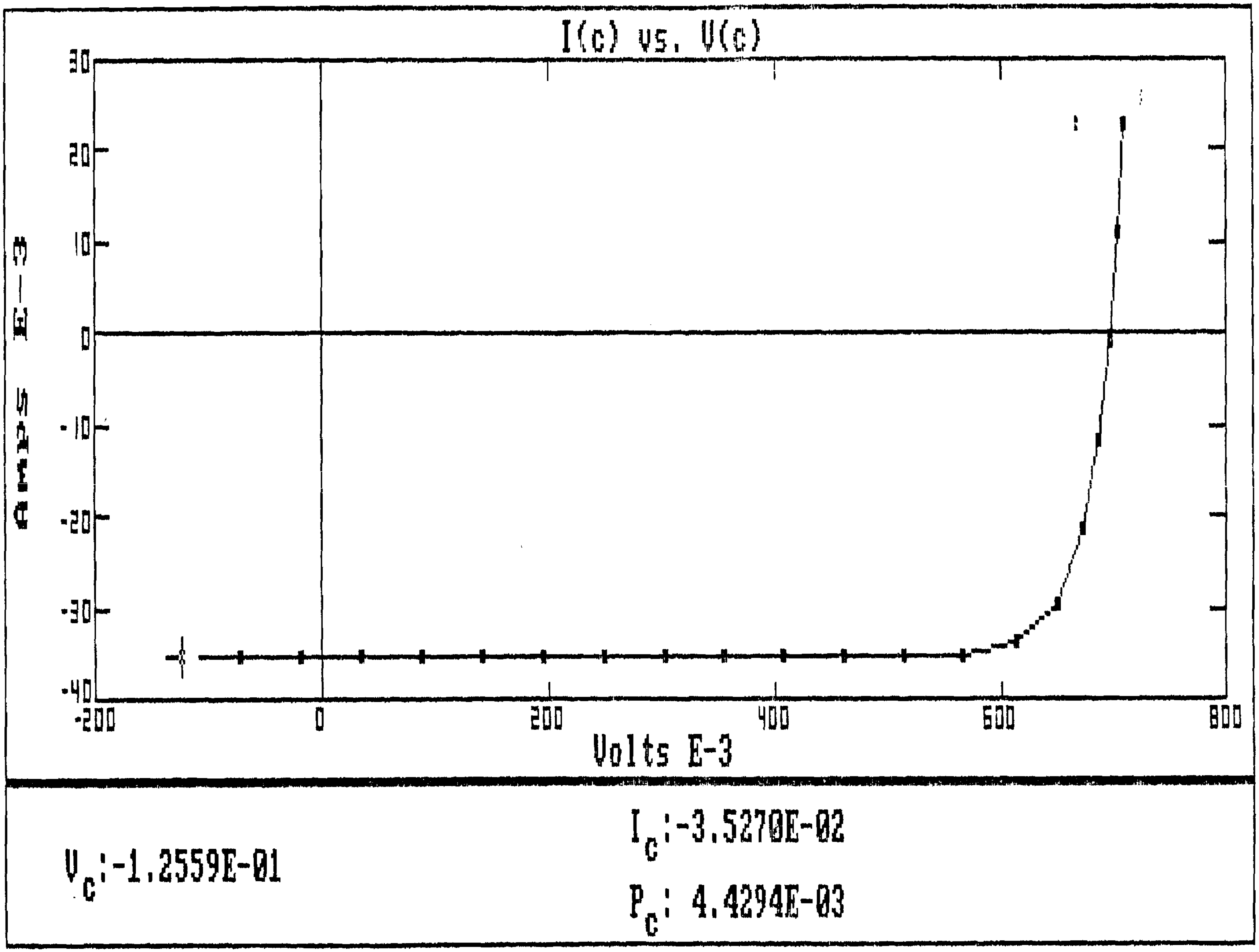
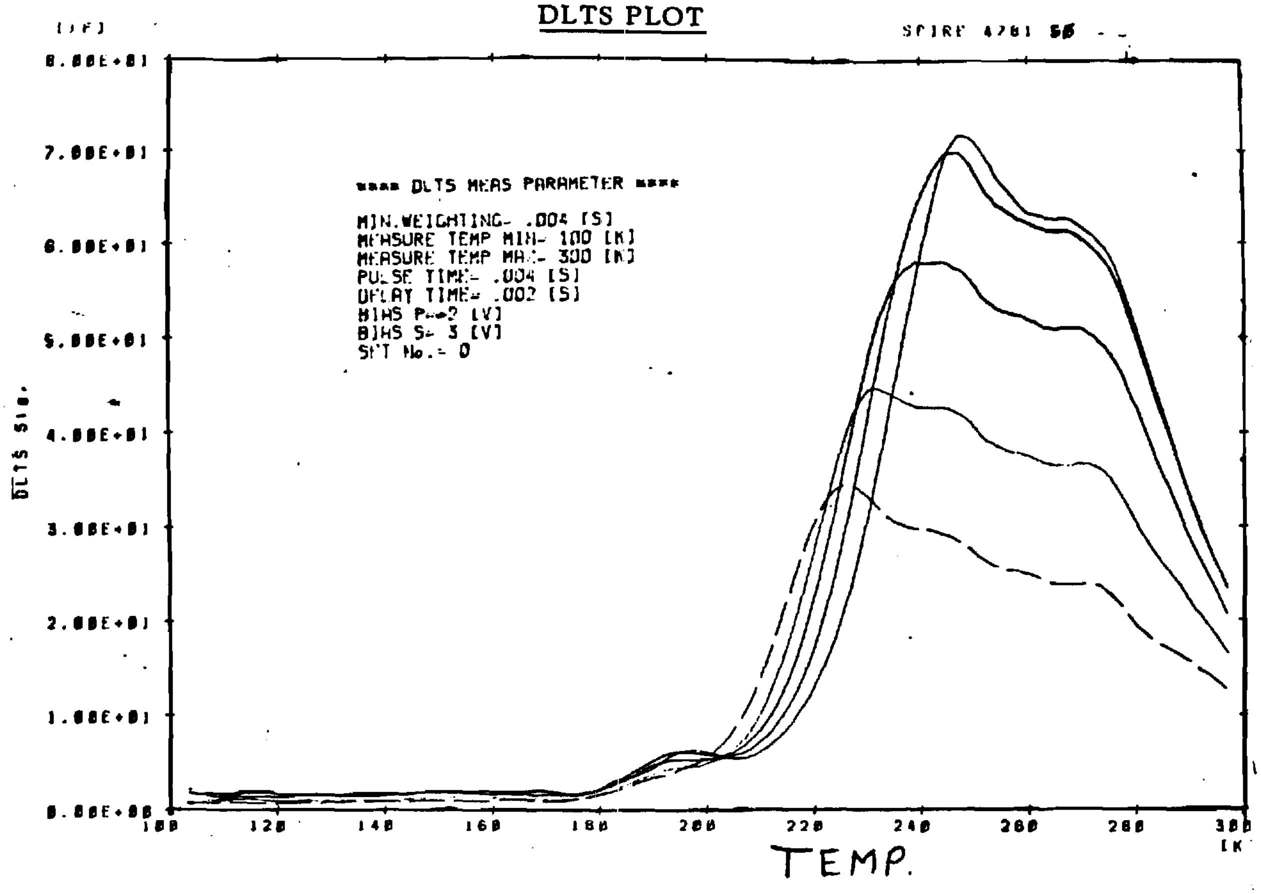

I(c) vs. V(c)
30
20
10
0
-10
-20
-30
-40
-200
0
200
400
600
800
Volts E-3
Amps E-3
V_c:-1.2559E-01
I_c:-3.5270E-02
P_c: 4.4294E-03

Figure 6

DLTS PLOT



ARRHENIUS PLOT

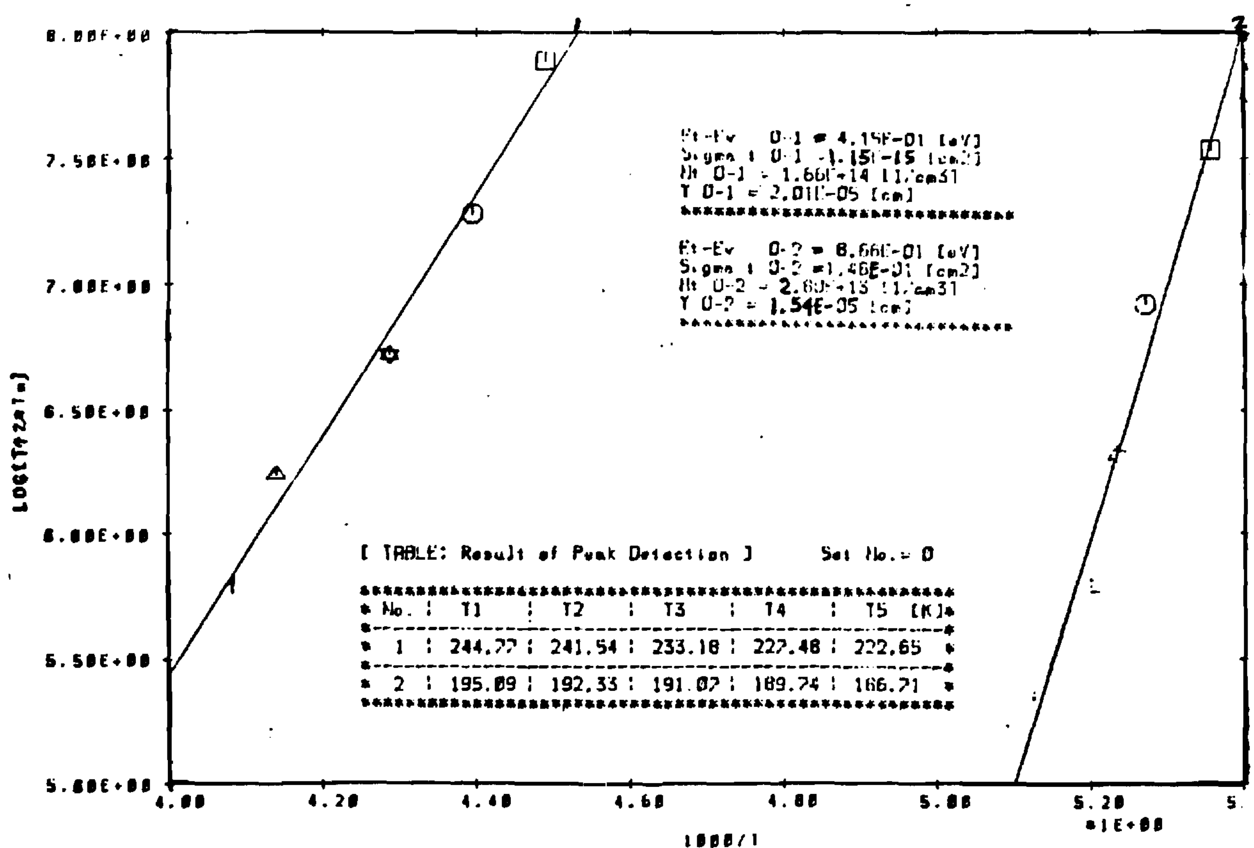


FIGURE 7: DLTS Spectra and Arrhenius plot for sample 5 which was ion implanted then Koh etched.

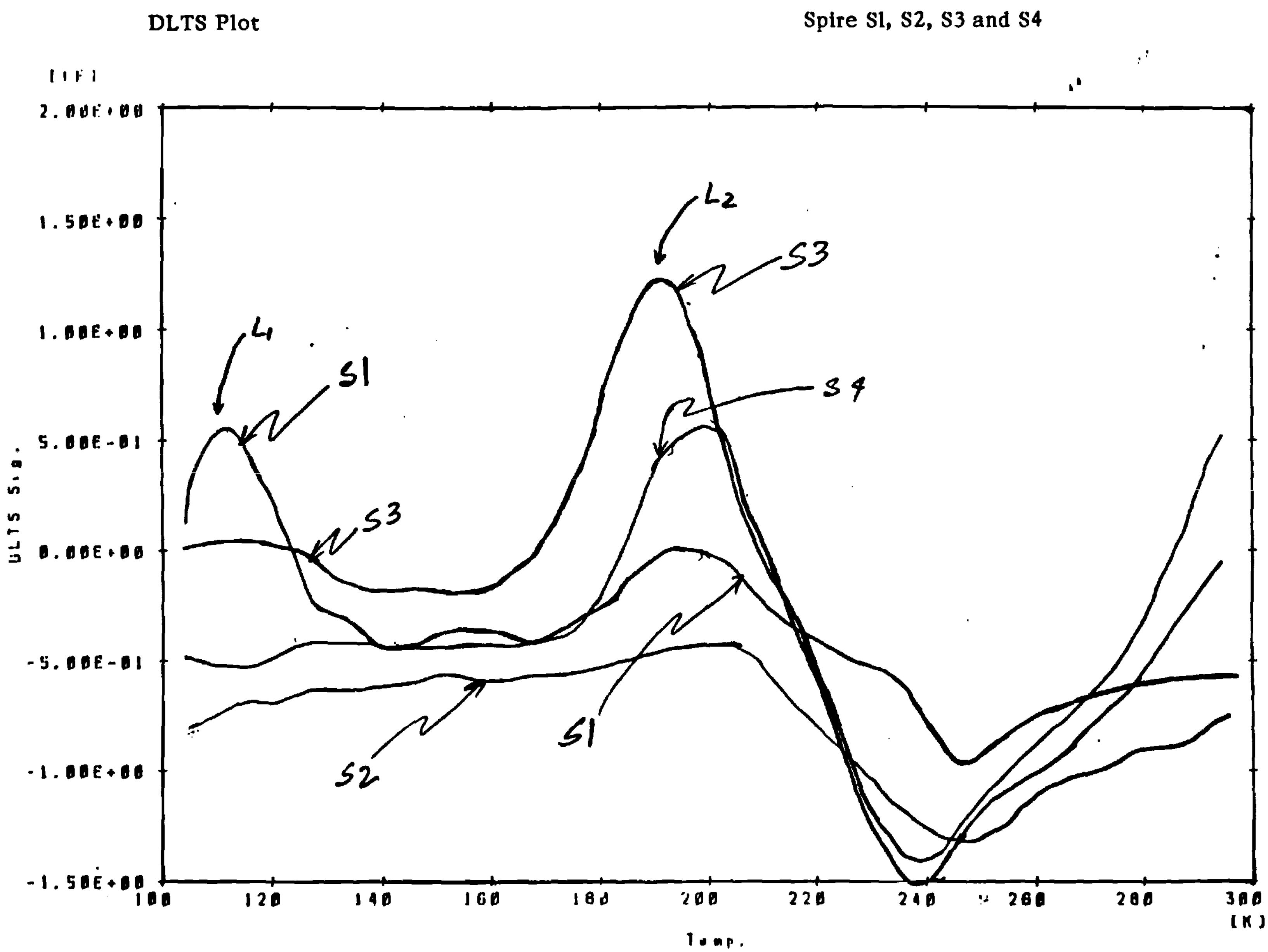


FIGURE 8: Comparison of DLTS Spectra for Samples S1, S2, S3 and S4. Sample description is given in Table 1.

HIGH EFFICIENCY CRYSTALLINE SOLAR CELL RESEARCH

A. Rohatgi

Third Report for the Period

April 1 to June 30, 1987

Solar Energy Research Institute

Contract No. XB 7-06070-1

GEORGIA INSTITUTE OF TECHNOLOGY
SCHOOL OF ELECTRICAL ENGINEERING
ATLANTA, GEORGIA 30332

Technical Progress on Textured Cells

In this report we describe our progress of using PC-1D model to include the effect of textured surface and high lifetime (1-10 ms) base. We find that with 1-2 Ω-cm silicon and 10 ms lifetime the program does not converge, therefore, we have used high resistivity silicon in these calculations and are looking into the ways of making the program to converge for low resistivity silicon. Model calculations shown in this report are consistent with the material quality that will be coming from Ciszek, Spire cell processing capabilities, and our design goal to approach 25% cell efficiency using the very best silicon available to date. We show in this report that ∿25% cells are possible with the quality of material grown by Ciszek provided the carrier lifetime can be maintained throughout the processing.

The purpose of this report is to show the possible cell parameters that may be obtained with better quality material that has become available. PC-1D, a device simulation progam, was used to calculate the cell parameters using 10 millisecond lifetime silicon, which is still not the highest lifetime claimed at this time. Parameters were also calculated at lower lifetimes in case the processing conditions degraded the initial lifetimes.

In the initial part of our calculations PC-1D was used to predict values for cells which have already been produced by Spire. At this early stage a number of different methods were attempted to reproduce the desired effects, these will be described later. Yet, the major stumbling block was the lack of some essential data on the Spire cells.

The first steps toward the simulation was to increase the light intensity and effectiveness of the back surface reflector. This had the desired effect of increasing the short circuit current, but it did not increase the open circuit voltage to the reported value. Calculations are compared to actual data in Table 1 for three cells, two with texturing and one which was not. Since so many parameters were unknown, and no clear way of checking the intensity was available yet this process was abandoned.

Approaching the problem from another angle the effective diffusion length was increased by a multiplication factor. Using a regular pyramid structure for the top surface the correction factor due to the increased absorption was 3. This again produced the correct value for the short circuit current, but the open circuit voltage obtained was higher than the reported value. Upon consultation with Paul Basore, the developer of PC-1D, it was determined that his method was totally incorrect. Due to the higher diffusion lengths the open circuit voltage may exceed that which is realistically achievable. So the approach was rejected and no values were tabulated.

In the conversation with Dr. Basore, it was suggested we wait until a report on light trapping was released by Sandia Lab. Using the equation in the report a short computer program, listed in the appendix, was developed to give the intensity and flux which would best represent the textured cells. Giving the program the width of the cell, the front and back surface reflections, and the front surface coverage, it will produce the required flux and an estimate of the intensity. The value calculated for the flux and PC-1D intensity are listed in Table 2, also included are values given in the Sandia report. Duplication of the cell values in the Sandia report was not attempted because the front and back surface recombination velocities for these cells was determined apriori. The method used is known but getting an exact match would be difficult and not of interest to us, as will be explained later.

Using our new knowledge for the intensity and the structure of the Spire cells new parameters were determined. Table 3 gives the values obtained when the cell width and lifetime were varied. All of the cells had the same configuration in that:

1) emitter width is 0.2 microns
2) emitter doping is complementary error with doping of 2E19
3) front surface coverage of 4.5%
4) front surface recombination velocity of 500 cm/sec
5) back surface field width of 2 microns
6) back surface doping of 2E18 and complementary error
7) back surface recombination velocity of 100 cm/sec
8) substrate was 200 ohm-cm
9) 0.04 ohm contact resistance
10) area of the cell is 1 cm

11) back surface reflector of 98% effectiveness

12) front surface internal reflector of 92% effectiveness

13) latest values for the auger coefficients of the carriers.

In all the cases notice that the front and back surface recombination velocities were kept constant. This is contrary to the procedure used by Dr. Basore, in which the emitter saturation current was kept constant. The reasoning behind keeping the velocities constant was due to the belief in constant processing. Processing of all the cells should be the same so passivation of the surface will depend upon the procedure not on the initial lifetime of the material. If at some point in the processing the lifetime is diminished the surface passivation should not be effected. Figure 1 illustrates the trend in the efficiencies of the cells as the lifetime is varied. The other parameters dependence upon lifetime and width are shown in figures 2 and 3. Values from the Sandia report are included, the differences are due to the surface recombination velocity and their cells had only a 3.5% surface coverage.

Figure 1 shows that as the cells are thinned down the efficiency will increase until a saturation is reached. The 10 millisecond lifetime material should be able to obtain efficiencies of greater than 24%. The width of the cell does not cause as dramatic an effect on the higher lifetime material as in the lower lifetime material. The two x's are for the simulations carried out by Dr. Basore, remember that different assumptions were made between the cells that we simulated and his. The open circuit voltage is shown, figure 2, to show the general trend that as the cell is thinned the voltage rises. As the lifetime increase the voltage rises for the same thickness of the cells. The amount of the effect of voltage rise is decreasing as the lifetime is increased. Finally figure 3 shows that as the cells are thinned the short circuit current density decreases. Also note that only when the cell is thicker does the increase in lifetime have an effect on the current density.

At this time work is continuing on simulating textured cells using 15 ohm-cm substrates which have a 10 millisecond lifetime. A problem of convergence has arisen which must be addressed before this may be reported. The future of this work should include changing the surface coverage, varying the doping profiles, and other cell characteristics. Also the short program for the intensity should be expanded to include lambertian design and the double perpendicular design which will give better light trapping characteristics to the cells.

Table 1.

This table is a comparison of PC-1D and the data supplied by SPIRE.
All of the cells have the following things in common:

1) Area is 4cm2
2) A front surface recombination velocity of 500 cm/sec
3) A back surface recombination velocity of 100 cm/sec
4) A junction depth of .2 microns
5) A surface doping concentration of 1E19
6) Cell 4760-8e is 254 microns wide, all others are 380 microns
7) Cell 4760-8e has a resistivity of .15 ohm-cm, all others are 10 ohm-cm

Cell	Source	ISC	JSC	VOC	PM	VM	IM	L	RE	BSR	Reflectio
4760-8e	PC-1D	0.1212	0.033	0.6415	0.6205	0.545	0.1138	137	0.2	0.95	0.15
4760-8e	PC-1D	0.1212	0.033	0.6405	0.4552	0.411	0.1105	137	1.5	0.95	0.15
4760-8e	SPIRE	0.12	0.03	0.589	0.359	0.359	0.097	137	?	?	?
4757-7d	PC-1D	0.15421	0.0385525	0.5996	0.74676	0.4994	0.14937	1122	0.2	1	0.085
4757-7d	PC-1D	0.15421	0.0385525	0.5999	0.47872	0.35888	0.13339	1122	1.5	1	0.085
4757-7d	SPIRE	0.1504	0.0376	0.612	0.8716	?	?	1122	?	?	0.085
4757-7f	PC-1D	0.15483	0.0387075	0.6119	0.081969	0.52466	0.15623	2000	0.2	1	0.085
4757-7f	PC-1D	This calculation would not converge						2000	1.5	1	0.085
4757-7f	PC-1D	0.15401	0.0385025	0.59969	0.073317	0.50185	0.14609	1000	0.2	1	0.085
4757-7f	PC-1D	0.15399	0.0384975	0.5969	0.046596	0.37371	0.12469	1000	1.5	1	0.085
4757-7f	PC-1D	0.1512	0.0378	0.59661	0.071819	0.50539	0.1421	1000	0.2	0.95	0.1
4757-7f	PC-1D	0.15119	0.0377975	0.595	0.046579	0.34788	0.13389	1000	1.5	0.95	0.1
4757-7f	SPIRE	0.163	0.0408	0.621	0.0777	0.506	0.154	?	?	?	?

Table 2. Fluxes and intensities for the simulation of textured cells of varing widths.

1 Sun Cells
Surface Coverage of 4.5%

Width microns	Flux	PC-1D flux	PC-1D intensity
200	2.5440E+17	2.5454E+17	0.997
254	2.5540E+17	2.5541E+17	0.989
381	2.5698E+17	2.5677E+17	0.976
500	2.5769E+17	2.5778E+17	0.969
635	2.5876E+17	2.5898E+17	0.965

1 Sun Cells
Surface Coverage of 3.5%

Width microns	Flux	PC-1D intensity	Source
200	2.5790E+17	0.997	Basore
200	2.5700E+17	0.997	Ga Tech
254	2.5810E+17	0.996	Ga Tech
381	2.5970E+17	0.99	Ga Tech
500	2.6060E+17	0.984	Basore
500	2.6060E+17	0.984	Ga Tech
635	2.6140E+17	0.975	Ga Tech

Table 3. Parameter of solar cells for a given lifetime when the width is varied.
These are 200 ohm-cm substrate cells.

1msec

width	Pmax	Voc	Jsc
635	20.18549	0.667	0.04141
500	20.79154	0.673	0.041276
381	21.38201	0.6795	0.041121
254	22.10190	0.688	0.040916
200	22.42477	0.69201	0.040767

2msec

width	Pmax	Voc	Jsc
635	21.64174	0.679	0.041443
500	22.08105	0.684	0.041281
381	22.51003	0.688	0.041125
254	22.99988	0.694	0.040918
200	23.20745	0.6975	0.040769

5msec

width	Pmax	Voc	Jsc
635	22.95360	0.6875	0.041467
500	23.20126	0.6905	0.041285
381	23.44640	0.694	0.041127
254	23.73480	0.6987	0.04092
200	23.79351	0.7005	0.04077

10msec

width	Pmax	Voc	Jsc
635	23.51674	0.6899	0.041478
500	23.66810	0.6925	0.041287
381	23.85324	0.6955	0.041128
254	23.99168	0.6999	0.040921
200	24.01421	0.7015	0.040771

Fig 1. Efficiency as a function of width

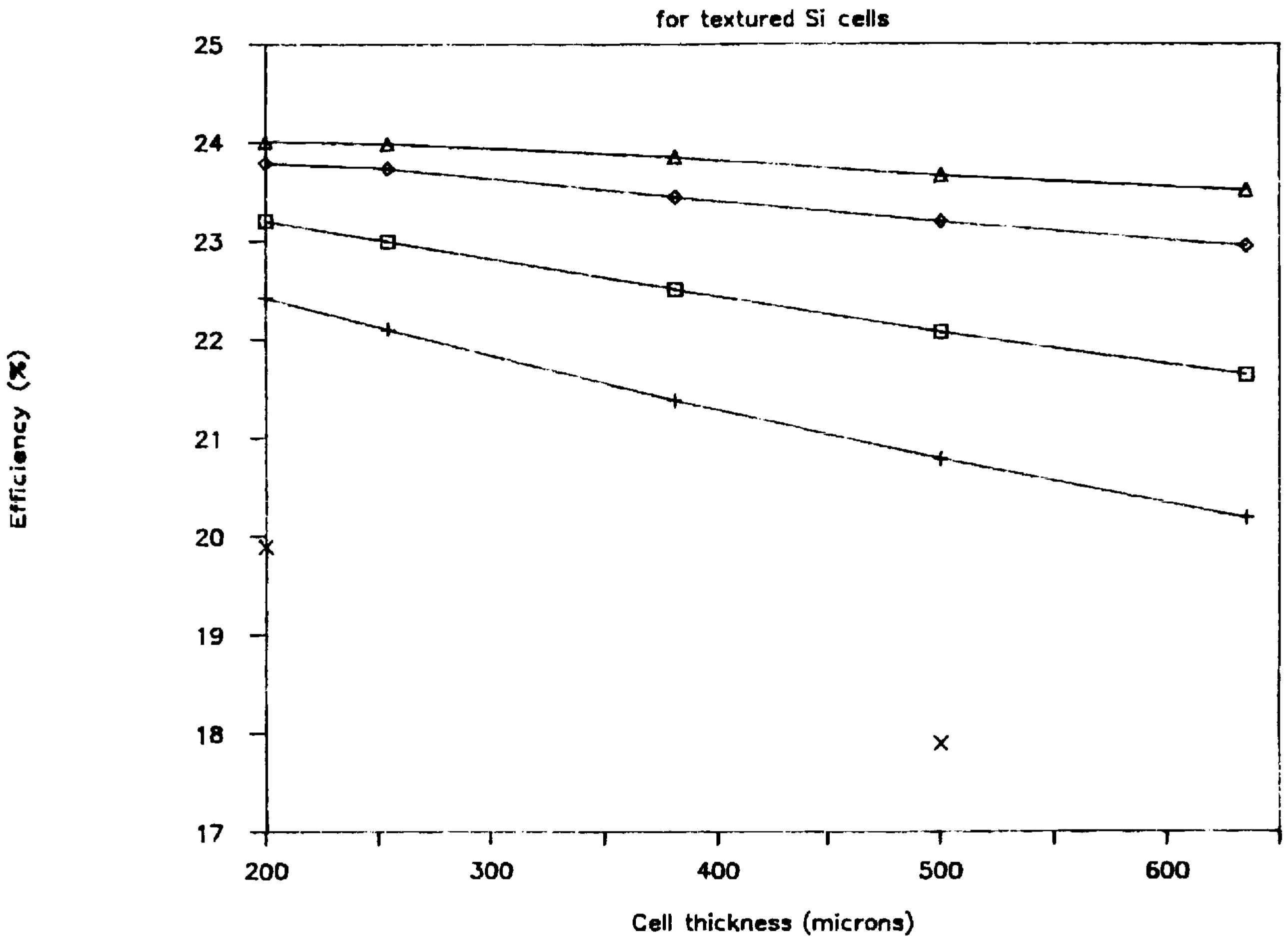


Fig 2. Voltage as a function of width

for textured Si cells

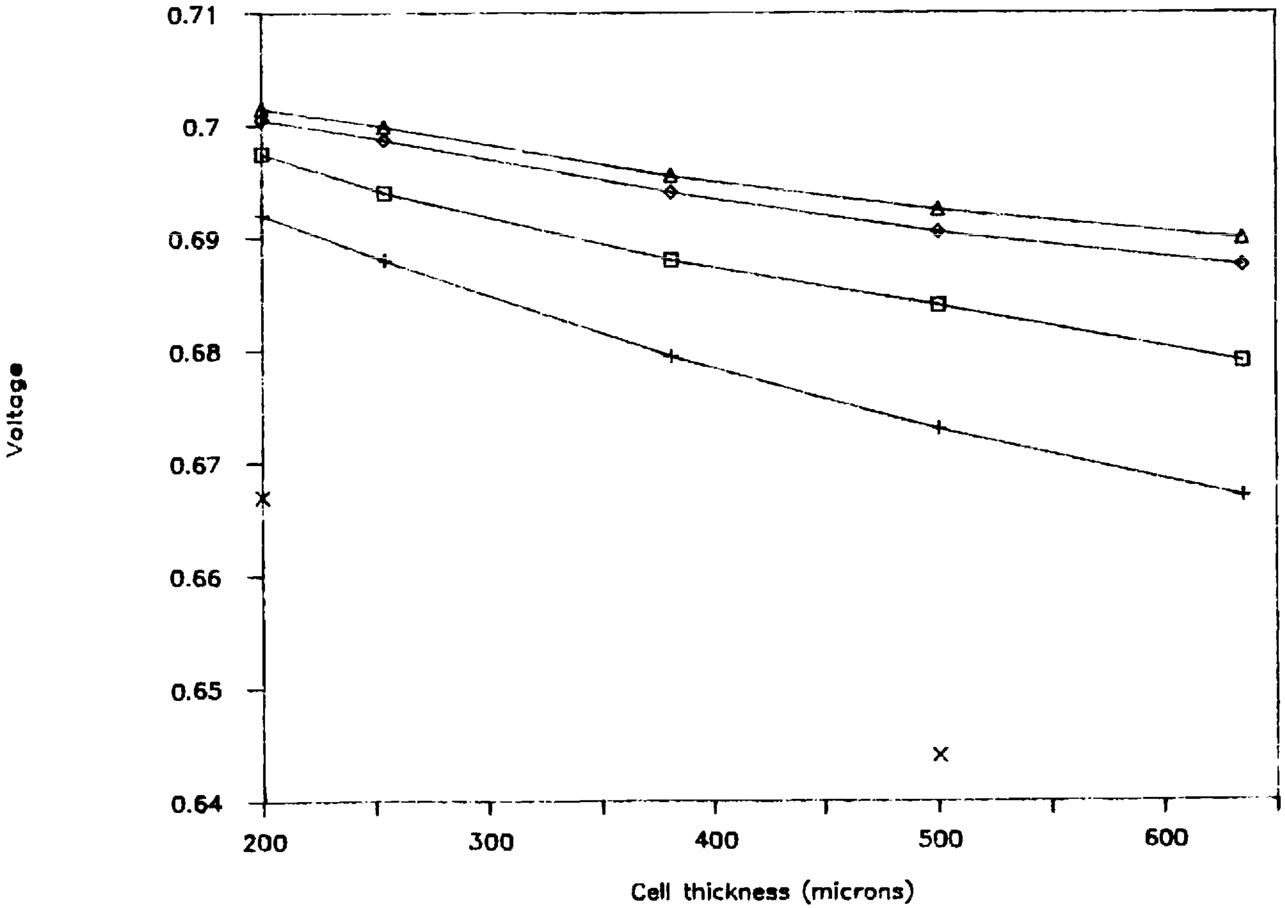
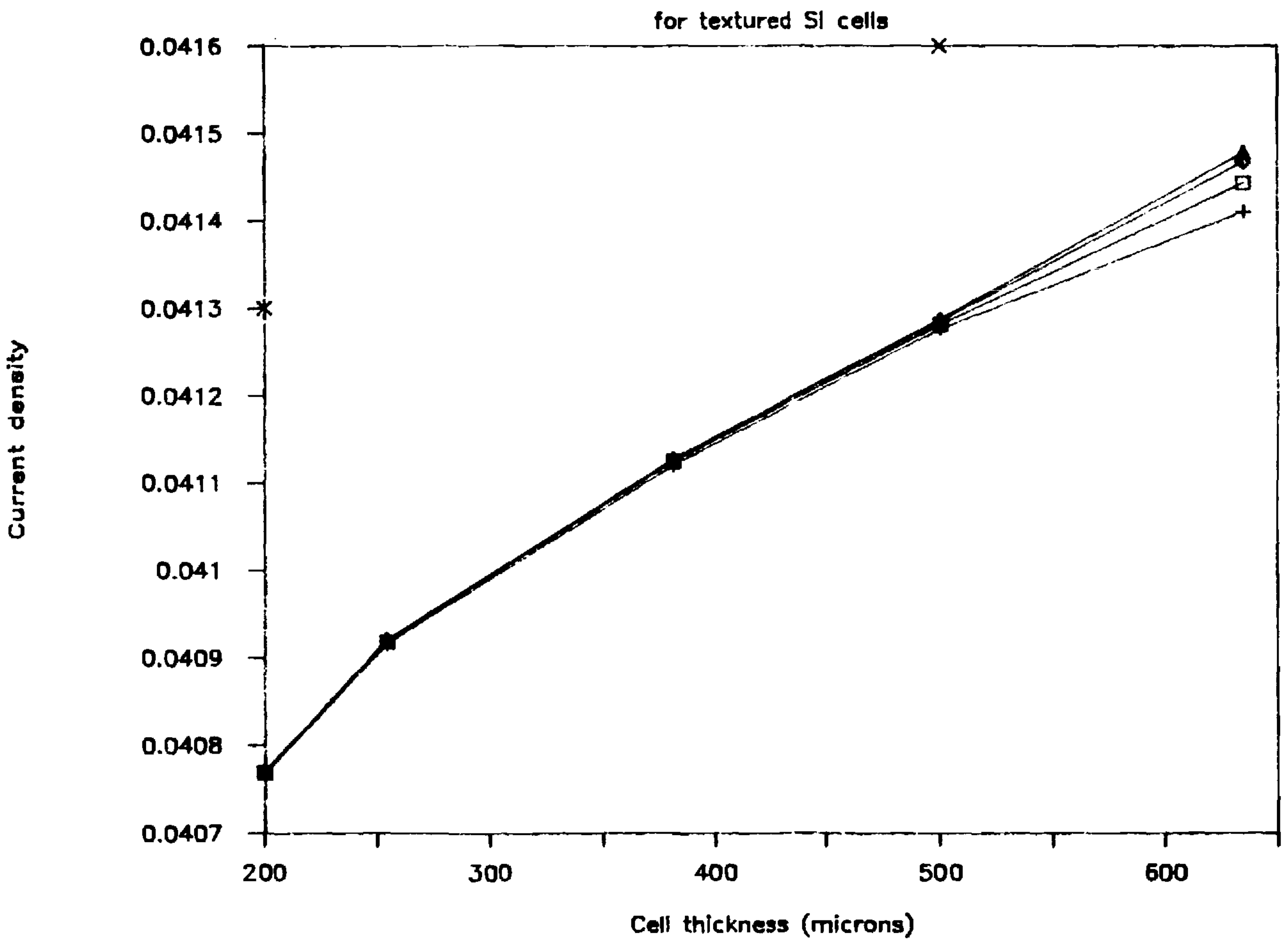


Fig 3. Current density as a fuction of width



II

APPENDIX

```
N=200:I=50:WD=50:E4=1.0E
DIM THE(N),LA(I),AL(I),AI(I),EB(I),A(I),EP(I),C(2)
FOR CC=0 TO I-1
READ LA(CC)
NEXT CC
READ EB(1),EB(2),EB(3),A(1),A(2),A(3),EP(1),EP(2),C(1),C(2)
CLS:LOCATE 12,30,0:PRINT"WHAT IS THE TEMPERATURE";
INPUT T
T=T+273.15:BE=7.021E-4:BA=1.108E-16:PB=6.17E-5:CLS
LOCATE 12,30,0:PRINT"WHAT IS THE WIDTH OF THE CELL";
INPUT W
CLS:
LOCATE 12,30,0:PRINT"WHAT IS THE BACK SURFACE REFLECTION";
INPUT BSR
CLS:LOCATE 12,30,0:PRINT"WHAT IS THE FRONT SURFACE REFLECTION";
INPUT FSR
CLS:LOCATE 12,30,0:PRINT"WHAT IS THE FRONT SURFACE COVERAGE";
INPUT FSC
CLS
FI=0.002/1.602E-19
FOR CC=1 TO 499 STEP 1
THE(CC)=1/((CC-0.5)/500)
NEXT CC
FOR CC=1 TO 2
EB(CC)=EB(CC)-(BE*(T^2)/(T+BA))
NEXT CC
FOR CC=0 TO I-1
AL(CC)=0
FOR C1=1 TO 2
FOR C2=1 TO 2
IF (1.2399/LA(CC)-EB(C1))<EP(C2) OR (1.2399/LA(CC)-EB(C1))<-EP(C2) THEN GO TO WHER
AB1=(1.2399/LA(CC)-EB(C1)+EP(C2))^2
AB2=(1.2399/LA(CC)-EB(C1)-EP(C2))^2
AB3=(EXP(EP(C2)/(K*T)))-1
AB4=1-(EXP(-EP(C2)/(K*T)))
AL(CC)=C(C2)*A(C1)*((AB1/AB3)+(AB2/AB4))+AL(CC)
WHER:NEXT C2
NEXT C1
BH=(1.2399/LA(CC)-EB(3))
IF BH<=0 THEN GO TO HERE
AL(CC)=AL(CC)+A(3)*((1.2399/LA(CC)-EB(3))^(1/2))
HERE:IF LA(CC)=1.12 THEN AL(CC)=0.5+AL(CC)
IF LA(CC)=1.19 THEN AL(CC)=0.9+AL(CC)
IF LA(CC)=1.22 THEN AL(CC)=0+AL(CC)
IF LA(CC)=1.26 THEN AL(CC)=0+AL(CC)
IF LA(CC)=1.31 THEN AL(CC)=0+AL(CC)
IF LA(CC)=1.51 THEN AL(CC)=0+AL(CC)
NEXT CC
RHO=0
FOR CC=0 TO I-1
FABS=0:FRET=0
FOR C1=0 TO N-1
TEM=(THE(C1))
TE1=EXP(-AL(CC)*W/TEM)
TE2=EXP(-2*AL(CC)*W/TEM)
FABS=FABS+((1-TE1)*(1+BSR*TE1))*TEM
FRET=FRET-BSR*TE2*TEM
NEXT C1
AI(CC)=(FABS/500)/(0.5-(FSR*FRET/500))
RHO=RHO+FI*LA(CC)*AI(CC)/1.23985
```

E-21-001

GEORGIA INSTITUTE OF TECHNOLOGY
SCHOOL OF ELECTRICAL ENGINEERING
ATLANTA, GEORGIA 30332

LEPHONE: (404) 894- 7337

March 30, 1988

Mr. John Benner
Solar Energy Research Institute
1617 Cole Blvd.
Golden, CO 80401-3393

Re: Contract No. XB-7-06070-1 under DE-AC02-83CH10093

Dear Mr. Benner:

Attached please find copies of the Final Report for the period 9/1/86-8/31/87 on the above referenced project.

If you have any questions, please feel free to contact me.

Sincerely,

Pam Majors
Research Administrator

pm
Attachments

cc: Margaret Lemke

HIGH EFFICIENCY CRYSTALLINE SOLAR CELL RESEARCH

A. Rohatgi, A.W. Smith, S.A. Ringel and G. Augustine

Annual Report for the Period
September 1, 1986 to August 31, 1987

Solar Energy Research Institute

Contract No. XB 7-06070-1

GEORGIA INSTITUTE OF TECHNOLOGY
SCHOOL OF ELECTRICAL ENGINEERING
ATLANTA, GEORGIA 30332

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1. INTRODUCTION

During the past several years, research in crystalline silicon has resulted in significant improvements in cell efficiency. Various aspects of the expertise needed for attaining greater than 20% efficient cells have been developed by different research groups in the United States. However, no single group has all the capabilities to produce >20% efficient and cost effective one-sun solar cells. The objective of this program was to provide a focal point for a coordinated approach which taps the expertise of several groups to design and produce high efficiency (>20%) silicon cells.

SERI was supposed to provide high lifetime silicon. Georgia Tech was supposed to characterize the material and use that information to design high efficiency cells (>20%) using various computer models available today. Spire Corporation was supposed to provide help in fabricating those cells.

A small effort was also devoted to GaAs cells with the objective of characterizing GaAs heteroface cells using approaches and tools which have been developed for silicon cells. Through modelling and analysis an attempt has been made to provide guidelines for making better GaAs cells.

This report summarizes the work done at Georgia Tech which includes:

(a) a comparison of various solar cell computer models such as PC-1D, SPCOLAY, SCAP-1D and SRV,

(b) designs of greater than 20% efficient cells using low resistivity silicon with Spire cell configuration,

(c) designs of cells with efficiency approaching 25% using the high lifetime (1-10 ms) material from SERI,

(d) DLTS analysis of Spire ion-implantation process to determine the cause of relatively low lifetimes in Spire cells,

(e) an analysis of MOCVD GaAs cells to provide guidelines for making higher efficiency (∿25%) heteroface GaAs one-sun cell.

2. TECHNICAL PROGRESS

2.1 Modelling of High Efficiency Solar Cells

2.1 (a) Comparison of PC-1D and SPCOLAY Models

In this section of the report we describe our progress in the area of solar cell modelling using both SPCOLAY[1] and PC-ID[2] computer models. The PC-1D was bought from Iowa University and SPCOLAY was obtained from the University of Pennsylvania, courtesy of M. Wolf. In addition, we have our own model for calculating Voc and the effect of surface recombination velocity.[3]

First an attempt was made to compare the output of the two models by incorporating advanced design features like surface passivation, heavy doping effects, reduced cell thickness, and back surface reflector. The PC-1D model was run using inputs that were virtually identical to the inputs for the SPCOLAY model in an attempt to determine the difference in the two programs. Table 1 shows some of the model inputs and the results of these calculations.

In the PC-1D model all of the donor and acceptor enhancement factors for the SRH lifetimes were set to zero. The SRH lifetime was then changed until the total minority carrier lifetime, which includes the SRH along with the Auger and the direct band-to-band recombination lifetimes, was set to a specified value. This made it possible to set the minority carrier lifetime to a value which when used in conjunction with the mobility would give the same diffusion length as used in the SPCOLAY model. The mobility of the carriers was found by doing a sample run and reading the value off the plot generated by PC-1D. Sample plots for the minority carrier lifetime and diffusion length as a function of distance are shown in figures 1 and 2. In addition figures 3 and

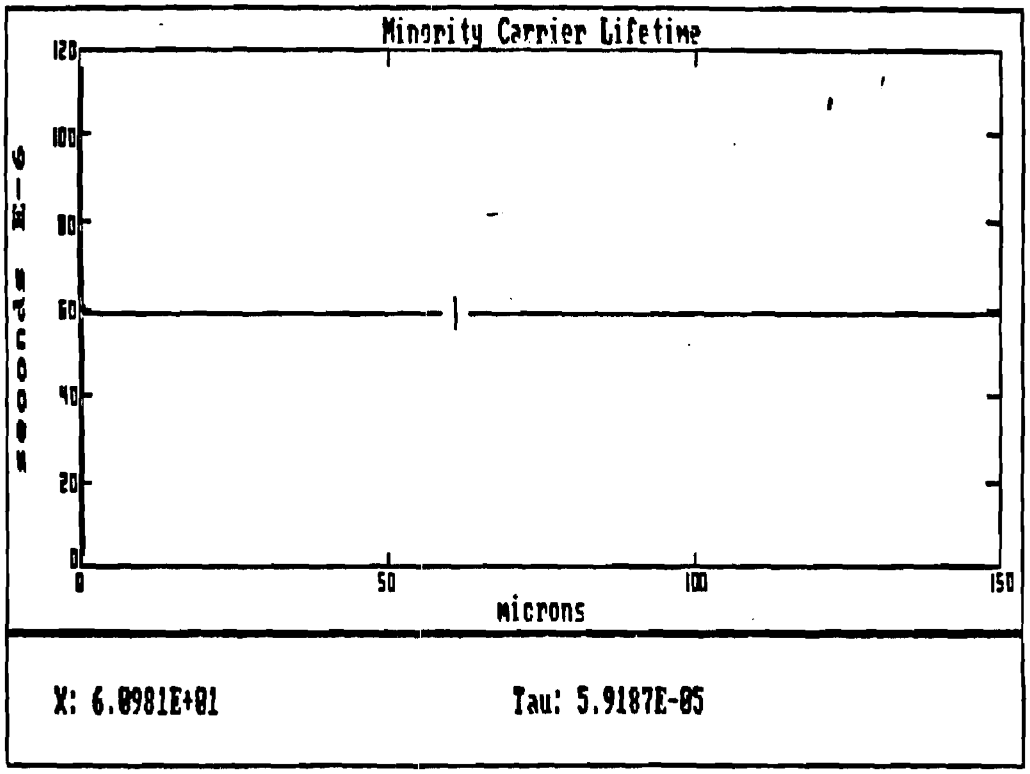


Figure 1: Minority carrier lifetime as a function of position.

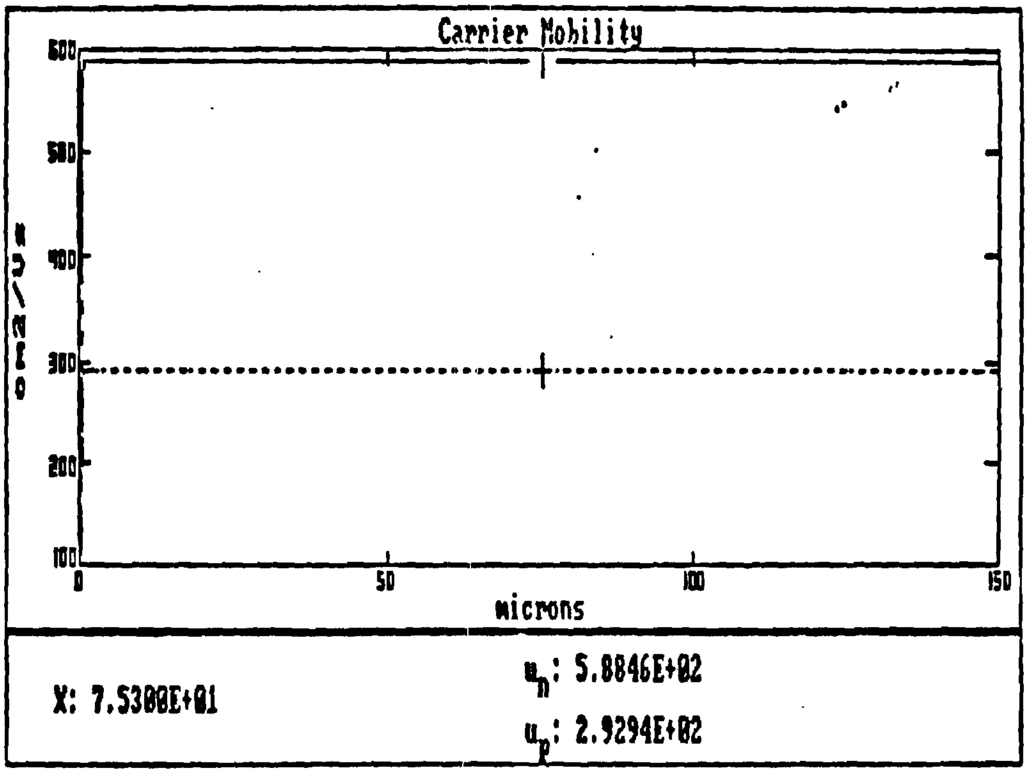


Figure 2: Carrier mobility as a function of position for both minority carriers and majority carriers.

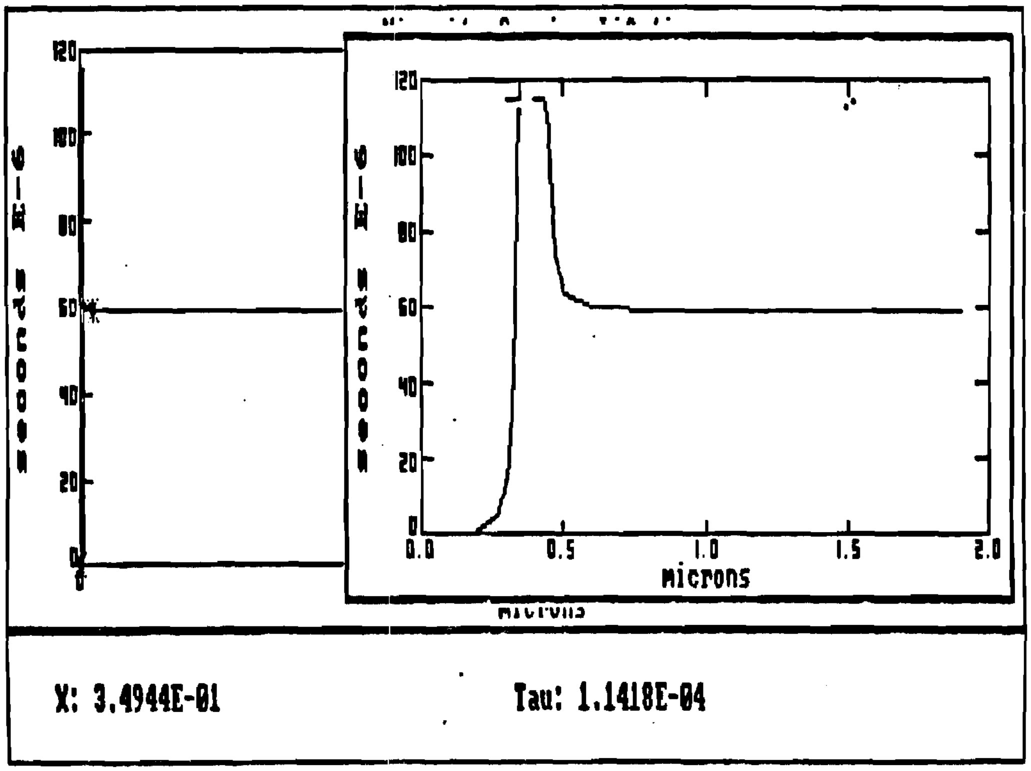


Figure 3: An expansion of minority carrier by time in emitter space-change region.

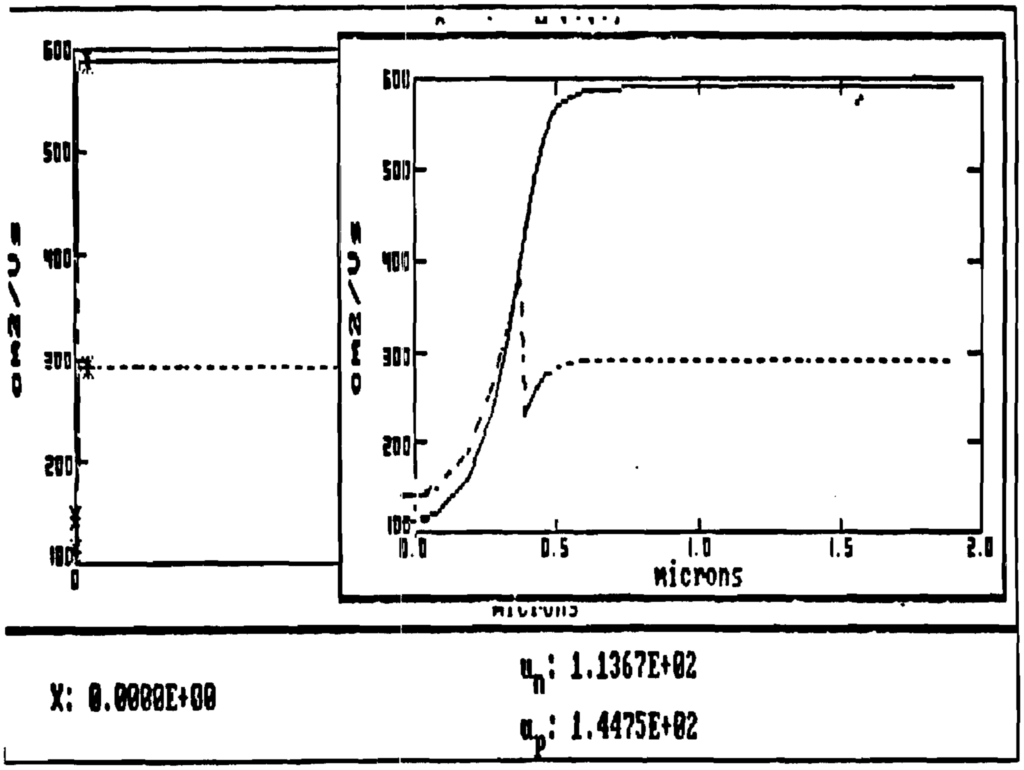


Figure 4: An expansion of carrier mobilities in emitter space change region.

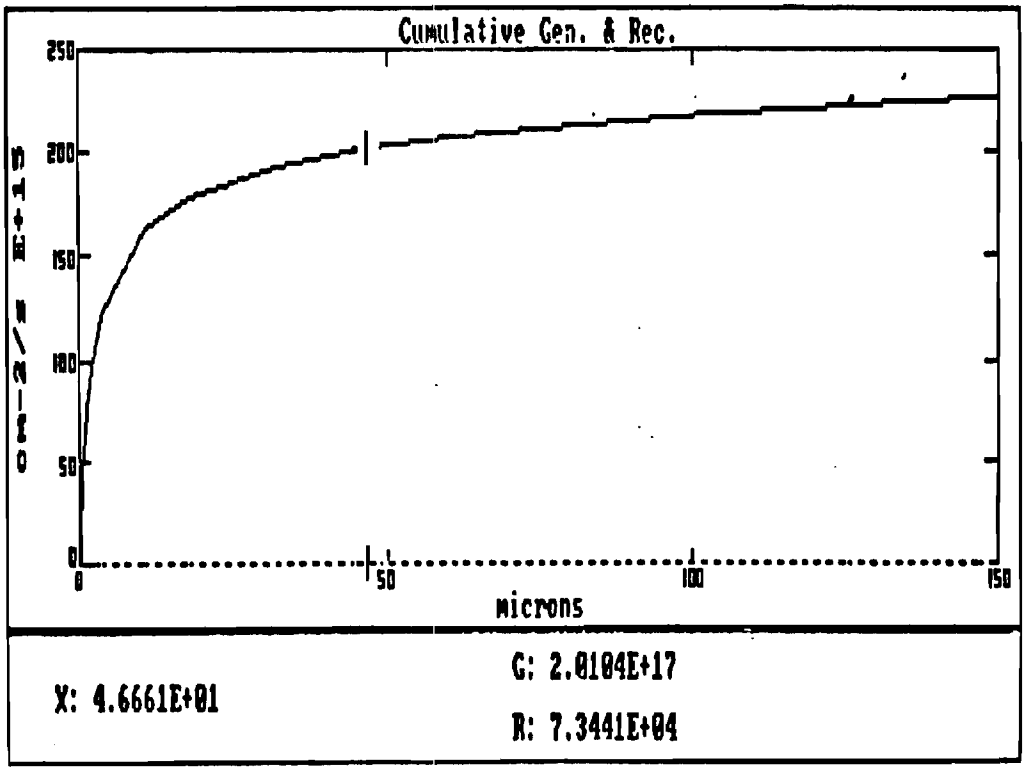


Figure 5: Cumulative generation and recombination as a function of position in the cell.

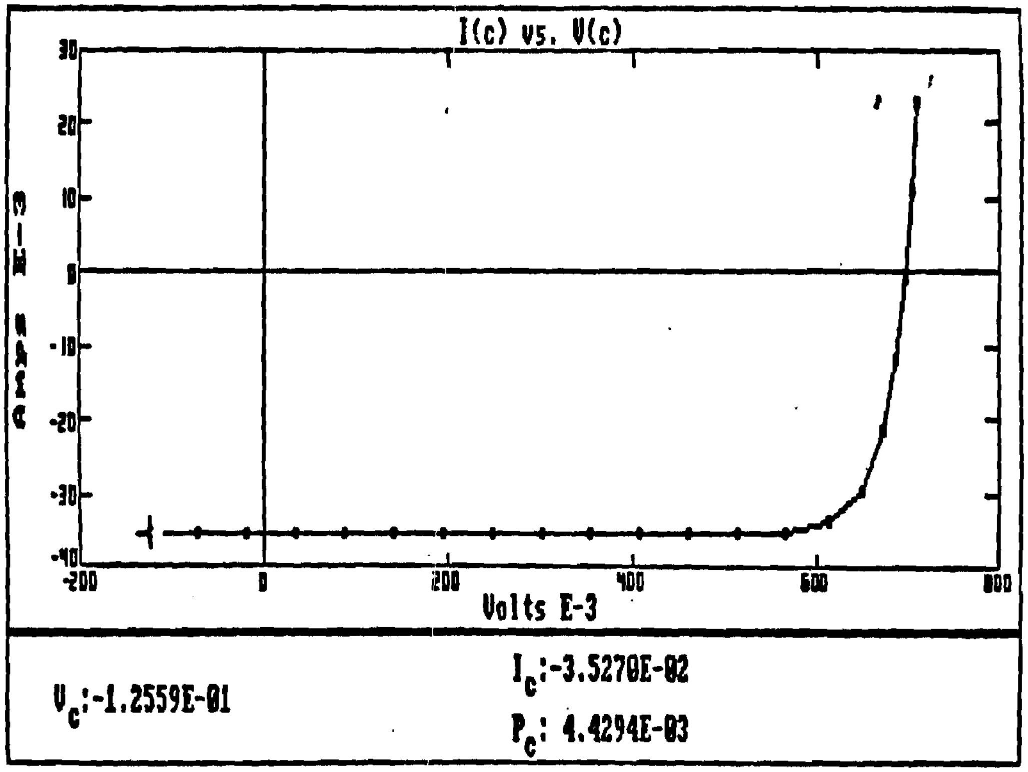


Figure 6: Calculated I-V curve for the cell.

4 show two plots which are blow-ups of the emitter region of the cell. The last two plots, figures 5 and 6, show the generation and recombination as a function of distance and the current-voltage curve of the solar cell. These are for the 20.8% efficient 150 micron cell (Table 1) with a back surface reflector and an emitter surface doping concentration of 1E19.

Table 1 shows the interplay between the design features and diffusion length. We find that PC-1D and SPCOLAY agree within 0.5% for the absolute value of efficiency. PC-1D generally predicts higher values of Voc and lower values for Jsc compared to SPCOLAY. In these calculations diffusion length was varied in the range of 150-300 microns, which is typical for the low resistivity Wacker float zone silicon cells.

According to these model calculations 20.3% cells can be realized with a diffusion length of 300 microns provided the cell is thinned down to 150 microns. The PC-1D model, which can take into account the back surface reflector effect, shows that an efficient BSR can give efficiency as high as 20.8%. Notice that these calculations were done for diffused solar cells with surface concentration of 2.0×10^{20} cm^{-3}.

2.1 (b) Comparison of PC-1D and SCAP-1D Models

The Scap-ID program is not available at Georgia Tech, therefore, we used Scap-1D model calculations done in a JPL report[9] to perform this task. We used identical inputs into the PC-1D model to calculate cell parameters. Calculations were done for the following cell design:

TABLE 1

PC-1D MODEL CALCULATIONS

These calculations were an attempt to match the model calculations from SPCOLAY. In all cases for PC-1D, the donar and acceptor enhancement of the SRH lifetime were set to zero, otherwise the lifetime could not be set to match the proper diffusion length as required. The efficiency was found using Wolf's fill factor formula. This could lead to some error in the PC-1D efficiency.

Model	Jun Depth	Ns	bsrv	fsrv	L(μm)	W(μm)	Loss	Voc (Volts)	Jsc (Amp)	Eff
spcolay	.2 μm	2.0E+20	26000	10000	168	375	0.1	0.61	0.0332	16.8
pc-ld	.2 μm	2.0E+20	26000	10000	168	375	0.1	0.64	0.0324	17.36
spcolay	.2 μm	2.0E+20	26000	10000	220	375	0.1	0.611	0.0341	17.2
pc-ld	.2 μm	2.0E+20	26000	10000	220	375	0.1	0.642	0.033	17.7
spcolay	.2 μm	2.0E+20	100	500	168	375	0.1	0.637	0.0339	18.0
pc-ld	.2 μm	2.0E+20	100	500	168	375	0.1	0.644	0.0328	17.66
spcolay	.2 μm	2.0E+20	100	500	220	375	0.1	0.639	0.0347	18.5
pc-ld	.2 μm	2.0E+20	100	500	220	375	0.1	0.647	0.0336	18.19
spcolay	.2 μm	1.0E+19	100	500	168	375	0.1	0.665	0.0341	19.0
pc-ld	.2 μm	1.0E+19	100	500	168	375	0.1	0.672	0.0329	18.61
spcolay	.2 μm	1.0E+19	100	500	250	375	0.1	0.676	0.0352	20.0
pc-ld	.2 μm	1.0E+19	100	500	250	375	0.1	0.683	0.0341	19.62
spcolay	.2 μm	1.0E+19	100	500	300	375	0.1	0.68	0.0361	20.5
pc-ld	.2 μm	1.0E+19	100	500	300	375	0.1	0.689	0.0345	20.08
spcolay	.2 μm	1.0E+19	100	500	300	250	0.1	0.683	0.0355	20.5
pc-ld	.2 μm	1.0E+10	100	500	300	250	0.1	0.692	0.0345	20.16
spcolay	.2 μm	1.0E+19	100	500	300	150	0.1	0.687	0.035	20.3
pc-ld	.2 μm	1.0E+19	100	500	300	150	0.1	0.696	0.034	20.03
pc-ld	bsm added	1.0E+19	100	500	300	150	0.1	0.698	0.03527	20.81

Passivated Thin Silicon Solar Cell Design Parameters

Doping Profile:	Complimentary Error Funcion
Front Surface Doping:	$1.0 \times 10^{18}/cm^3$
Front Junction Depth:	0.2μm
Shadowing (including reflection):	7%
Bulk Doping (B):	$5 \times 10^{17}/cm^3$
Cell Thickness:	100μm
Back Surface Reflector:	Provided
Illumination:	100 mW/cm^2 (AM 1.5)

Results are summarized below for three different cases.

(1) Comparison of scapld and pc-1d with all the above parameters. Recombination velocities were 100cm/sec at front and back with back reflector, Auger and bgn effects, and 7% reflection loss.

model	Voc	Jsc	FF	Eff
scapld	0.696	36.71	0.845	21.59
pc-1d	0.713	36.08	0.848	21.82

(2) Comparison of scapld and pc-1d with all the above parameters. Recombination velocities of 0 cm/sec, no reflection losses, with Auger and bandgap narrowing effects and SRH lifetime of 250 usec.

model	Voc	Jsc	FF	Effic.
scapld	0.793	40.47	0.858	27.55
pc-1d	0.762	39.27	0.8535	25.29

(3) Comparison of scapld and pc-1d with all the same parameters. Recombination velocities of 0 cm/sec, no reflection losses, and Auger and bandgap narrowing effects were excluded. SRH lifetime was set to 20 μsec.

2.1 (c) Comparison of PC-1D and Surface Recombination Velocity (SRV) Models

Rohatgi and Davis developed a simple one dimensional model based on internal recombination velocity[2]. With the help of this model one can calculate the recombination velocities at the junction edges, starting with the surface recombination velocity. Leakage current and Voc are then calculated from

$$Jo = \frac{qni^2}{N_A} \; Sejb + \frac{qni^2}{N_D} \; Seje \text{ and } Voc = \frac{KT}{q} \; \ln \left(\frac{Jsc}{Jo} + 1\right).$$

This model uses a measured or calculated values of Jsc from other programs to give Voc. Since SRV model is only good for Voc calculations, a comparison of Voc calculated from PC-1D and SRV is shown below using the same inputs to both the models.

(1) The diffusion lengths were not adjusted in PC-1D but left to the default values. Measured values, when available, were used for comparison. Cell with heavy doping effects but no surface passivation.

model	Voc	Jsc	FF	Eff
SRV	0.582	33.40	0.823	16.01
pc-1d	0.588	37.51	0.825	18.20

(2) Cell with surface passivation and heavy doping.

model	Voc	Jsc	FF	Eff
SRV	0.6	36.20	0.829	18.00
pc-1d	0.6	38.97	0.829	19.38

2.1 (d) Modelling of High Efficiency Textured Cells Using Spire's Cell Design

In this section of the report PC-1D model was used to predict performance of the cells which have already been produced at Spire. Once a good match was obtained, we made some modifications in material parameters and cell design without using unreasonable material and process parameters, to develop designs for solar cells approaching 25% efficiencies.

We acquired most of the necessary cell data and material parameters on Spire's textured cells and tried different methods to account for the textured surface in PC-1D model to match the cell data. The first method of simulation was to increase the light intensity and effectiveness of the back surface reflector to account for the textured surface effects. This showed the desired effect of increasing the short circuit current, but it did not increase the open circuit voltage to the reported value. Calculations are compared to the actual data in Table 2 for three cells, two with textured surface (4757-d and 4757-f) and one without (4760-Be). In addition to the poor match between the predicted and measured values, several parameters were unknown (Table 2), and no clear way of checking the accuracy of the simulated intensity change was available, therefore this process was abandoned.

To approach the problem from another angle, the effective diffusion length was increased by a multiplication factor. Using a regular pyramid structure for the top surface the correction factor due to the increased

TABLE 2

This table is a comparison of PC-1D and the data supplied by SPIRE. All of the cells have the following things in common:

(1) Area is $4cm^2$
(2) A front surface recombinatio velocity of 500 cm/sec
(3) A back surface recombination velocity of 100 cm/sec
(4) A junction depth of .2 microns
(5) A surface doping concentration of 1E19
(6) Cell 4760-Be is 254 microns wide, all others are 380 microns
(7) Cell 4760-Be has a resistivity of .15 ohm-ca, all others are 10 ohm-cm.

Cell	Source	ISC	JSC	VOC	PM	VM	IM	L	RE	BSR	Reflection
4760-Be	PC-1D	0.1212	0.033	0.6415	0.6205	0.545	0.1138	137	0.2	0.95	0.15
4760-Be	PC-1D	0.1212	0.033	0.6405	0.4552	0.411	0.1105	137	1.5	0.95	0.15
4760-Be	SPIRE	0.12	0.03	0.589	0.359	0.359	0.097	137	?	?	?
4757-7d	PC-1D	0.15421	0.0385525	0.5996	0.74676	0.4994	0.14937	1122	0.2	1.0	0.085
4757-7d	PC-1D	0.15421	0.0385525	0.5999	0.47872	0.35888	0.13339	1122	1.5	1.0	0.085
4757-7d	SPIRE	0.1504	0.0376	0.612	0.8716	?	?	1122	?	?	0.085
4757-7f	PC-1D	0.15483	0.0387075	0.6119	0.081969	0.52466	0.15623	2000	0.2	1.0	0.085
4757-7f	PC-1D		This calculation would not converge					2000	1.5	1.0	0.085
4757-7f	PC-1D	0.15401	0.0385025	0.59969	0.073317	0.50185	0.14609	1000	0.2	1.0	0.085
4757-7f	PC-1D	0.15399	0.0384975	0.5969	0.046596	0.37371	0.12469	1000	1.5	1.0	0.085
4757-7f	PC-1D	0.1512	0.0378	0.59661	0.071819	0.50539	0.1421	1000	0.2	0.95	0.1
4757-7f	PC-1D	0.15119	0.0377975	0.595	0.046579	0.34788	0.13389	1000	1.5	0.95	0.1
4757-7f	SPIRE	0.163	0.0408	0.621	0.0777	0.506	0.154	?	?	?	?

absorption was $\sqrt{3}$. This again produced the correct value for the short circuit current, but the open circuit voltage obtained was higher than the reported value. Upon consultation with Paul Basore, the developer of PC-1D, it was determined that this approach was incorrect because due to the higher diffusion lengths the open circuit voltage may exceed that which is realistically achievable. So the approach was rejected and no values were tabulated.

Finally, Dr. Basore brought to our attention a report on light trapping that was released by Sandia Lab. Using the equations in the report, a short computer program listed in the appendix was developed to give the intensity and flux which would best represent the textured cells. Given the width of the cell, front and back surface reflections, and the front surface coverage, the program will produce the required flux and an estimate of the intensity to account for the textured surface effects. The values calculated for the flux and PC-1D intensity are listed in Table 3, along with the values given in the Sandia report. We have assumed that surface recombination velocities depended upon the processing parameters and not on the final lifetime in the material. This is the opposite of the method used by Sandia, in which the surface recombination velocity was dictated by assuming a specific dark current and the lifetime was used to back calculate the recombination velocity.

Using this knowledge base for the intensity and the structure of the Spire cells, new material and device parameters were determined to achieve ∿25% cell efficiency. Table 4 gives the values of parameters obtained when the cell width and lifetime were varied in a 200 ohm-cm material using the cell configuration of Table 5. In all cases, notice that the front and back surface recombination velocities were kept constant, regardless of the final lifetime in the material. If at some point in processing the lifetime is diminished, the surface passivation should not be effected. Figure 7 illustrates the trend in the cell

Table 3. Fluxes and intensities for the simulation of textured cells of varing widths. The BSR is 98% effective and the front surface is 92%.

1 Sun Cells
Surface coverage of 4.5%

Width microns	Flux	PC-1D flux	PC-1D intensity
200	2.5440E17	2.5454E17	0.997
254	2.5540e17	2.5541e17	0.989
381	2.5698e17	2.5677e17	0.976
500	2.5769e17	2.5778e17	0.969
635	2.5876e17	2.5898e17	0.965

1 Sun Cells
Surface coverage of 3.5%

Width microns	Flux	PC-1D intensity	Source
200	2.5790E17	0.997	Basore
200	2.5700E17	0.997	Ga. Tech.
254	2.5810E17	0.996	Ga. Tech.
381	2.5970E17	0.990	Ga. Tech.
500	2.6060E17	0.984	Basore
500	2.6060E17	0.984	Ga. Tech.
635	2.6140E17	0.975	Ga. Tech.

TABLE 4

Parameter of Solar Cells for a Given Lifetime When the Width is Varied

1 msec

Width	Pmax	Voc	Jsc
635	20.18549	0.667	0.04141
500	20.79154	0.673	0.041276
381	21.38201	0.6795	0.041121
254	22.10190	0.688	0.040916
200	22.42477	0.69201	0.040767

2 msec

Width	Pmax	Voc	Jsc
635	21.64174	0.679	0.041443
500	22.08105	0.684	0.041281
381	22.51003	0.688	0.041125
254	22.99988	0.694	0.040918
200	23.20745	0.6975	0.040769

5 msec

Width	Pmax	Voc	Jsc
635	22.95360	0.6875	0.041467
500	23.20126	0.6905	0.041285
381	23.44640	0.694	0.041127
254	23.73480	0.6987	0.04092
200	23.79351	0.7005	0.04077

10 msec

Width	Pmax	Voc	Jsc
635	23.51674	0.6899	0.041478
500	23.66810	0.6925	0.041287
381	23.85324	0.6955	0.041128
254	23.99168	0.6999	0.040921
200	24.01421	0.7015	0.040771

These are 200 ohm-cm substrate cells.

Table 5. Cell design parameters used in the simulation of high efficiency textured cells

1) emitter width is 0.2 microns
2) emitter doping is complementary error with doping of 2E19
3) front surface coverage of 4.5%
4) front surface recombination velocity is variable
5) back surface field width of 2 microns
6) back surface doping of 2E18 and complementary error
7) back surface recombination velocity is variable
8) substrates were 15 or 200 ohm-cm resistivity
9) series resistance was either 0.04 or 0.2 ohms
10) cell area of 1 cm^2
11) back surface reflector of 98% effectiveness
12) front surface internal reflector of 92% effectiveness
13) latest values for the Auger coefficients of the carriers
14) n type emitter
15) p type base and buffer

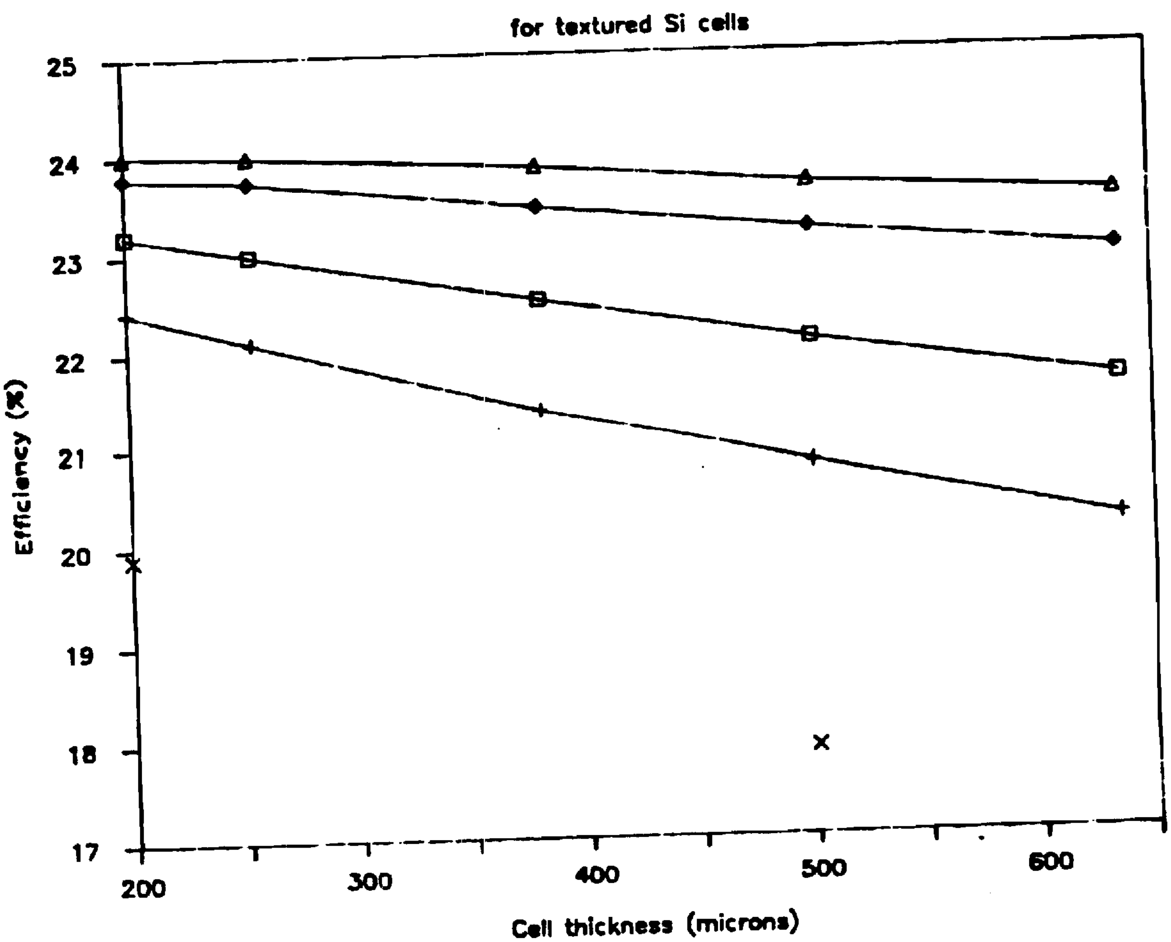


Fig 7 Efficiency as a function of width

efficiencies as the lifetime is varied from 1ms to 10ms. The other solar cell parameter dependence upon lifetime and width are shown in figures 8 and 9. Values from the Sandia report are also included, the differences are primarily due to the surface recombination velocity although their cells had a 3.5% coverage while ours had 4.5% coverage.

Figure 7 shows that as the cells are thinned down, the efficiency first increases and then tends to saturate. The 10 millisecond lifetime material is able to give efficiencies greater than 24%. The width of the cell does not cause as dramatic an effect in the higher lifetime material as in the case of lower lifetime material. The two x's are for the simulations carried out by Dr. Basore, recalling that different assumptions were made between our cells and his. The open circuit voltage, Figure 8, rises as the cell is thinned down. An increase in lifetime also increases the voltage for any given thickness of the cells, however, the relative increase in the voltage decreases as the lifetime increases. Finally Figure 9 shows that as these cells are thinned down, the short circuit current density decreases. Also note that only when the cell is thick (>500 μm), the increase in lifetime has an effect on the current density.

The next section describes our work on simulating textured cells using 15 ohm-cm and 200 ohm-cm substrates which have a lifetime in the range of 1 to 10 millisecond.

2.1 (e) Designs of ∿25% Efficient Textured Solar Cells Using High Lifetime Silicon Material from SERI

In this part of the report we describe our progress on using PC-1D model to include the effect of Lambertian textured surface and high lifetime (1-10 ms) base. We found that with 1-2 ohm-cm silicon and 10 ms lifetime the PC-1D program does not converge, therefore we have

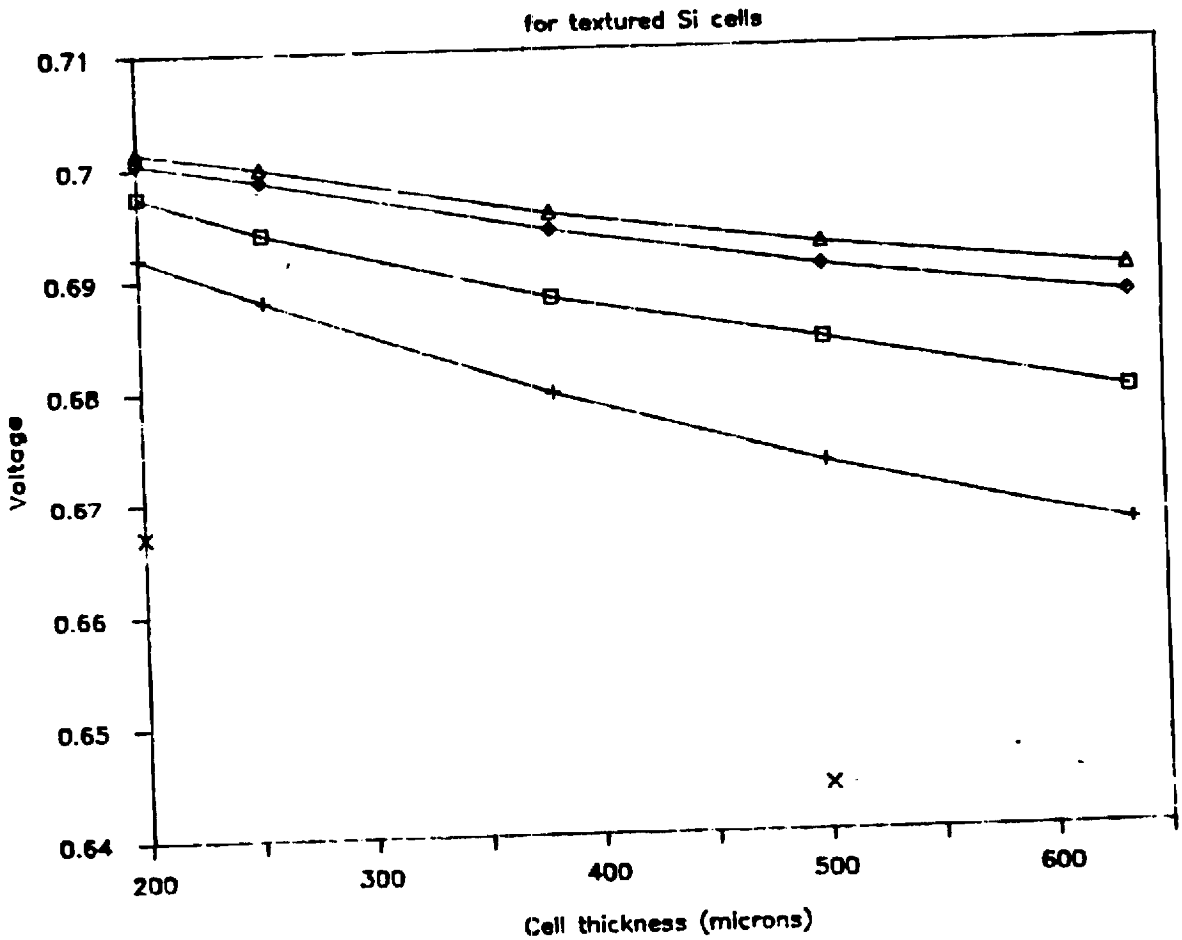


Fig 8 Voltage as a function of width

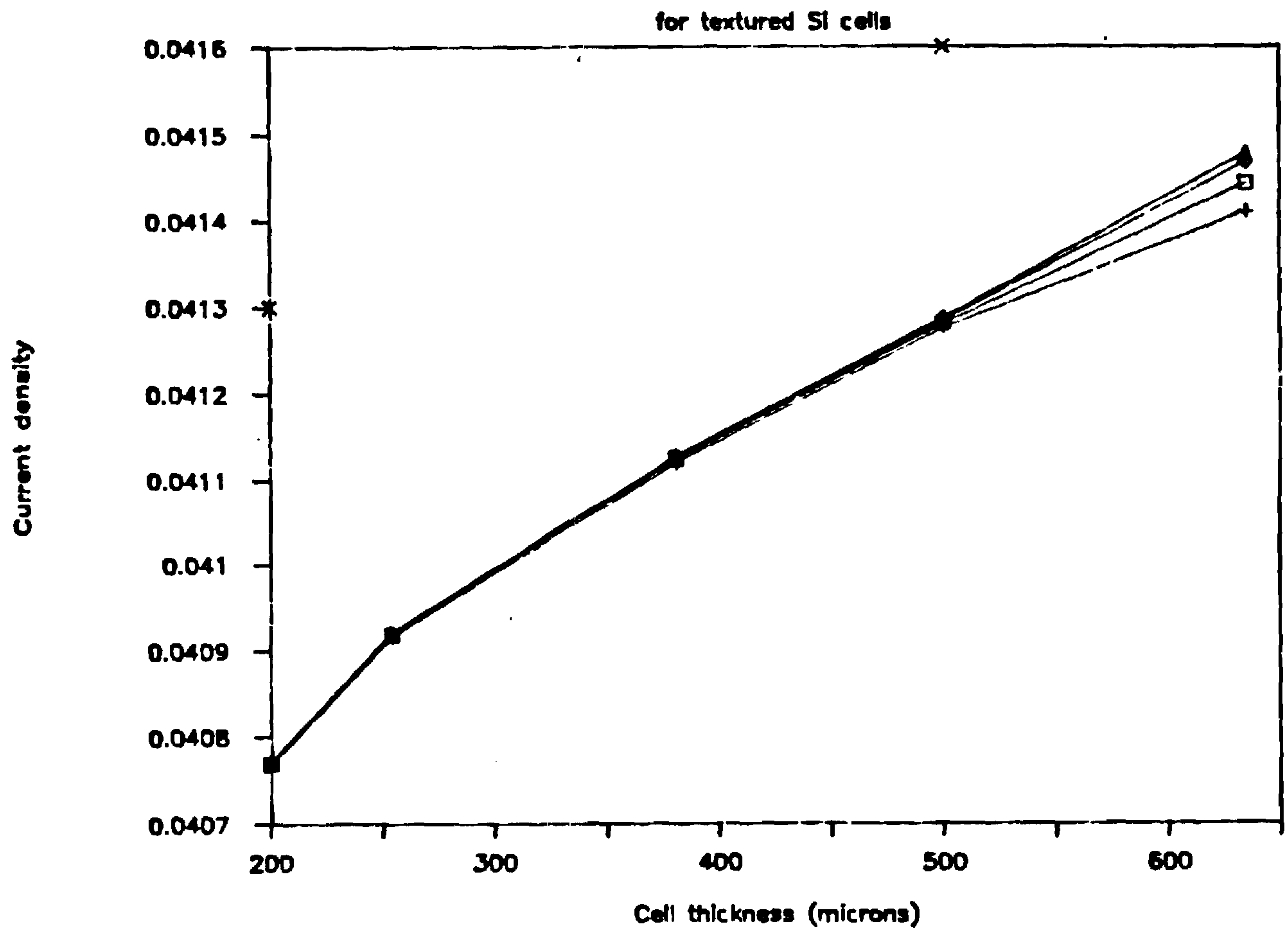


Fig 9 Current density as a fuction of width

used higher resistivity silicon (15-200 ohm-cm) in these calculations and are now looking into the ways of making the program to converge for high-lifetime low resistivity silicon. Model calculations shown in this report are consistent with the high lifetime material grown by Ciszek, Spire cell processing capabilities, and our design goal to approach 25% cell efficiency using the very best silicon available to date. We show in this section that ∿25% efficient cells are indeed possible with the high quality of material grown by Ciszek provided the carrier lifetime can be maintained throughout the processing.

The PC-1D model was used to calculate the cell parameters using 10 millisecond lifetime silicon. Parameters were also calculated for lower lifetimes in case the processing degraded the initial lifetimes. The basic cell characteristics and design parameters assumed are given in Table 5. Selected parameters were varied one at a time to see their effect on the cell performance and to provide practical guidelines for achieving very high efficiency cells from high lifetime silicon material being grown by Ciszek.

PC-1D was setup to simulate textured solar cells with the objective of achieving the maximum efficiency by using reasonable parameters for the cell. The cell configuration in Table 5 is very similar to the cells fabricated by Spire. Every attempt was made to keep the device design and material parameters within the practical range. The lifetime, cell width, surface condition, base resistivity, and series resistance were considered as variable quantities to optimize the cell efficiency. The results of the model calculations are tabulated in Tables 6 through 13. These values are then plotted for comparison in Figures 10 through 30. Consistent with Ciszek's material, calculations were performed for 15 ohm-cm and 200 ohm-cm material with lifetimes in the range of 1-10 milliseconds.

Table 6

Parameters of cell when the lifetime is specified but the width is variable. These cells are on 200 ohm-cm substrates with FSRV=100 and BSRV=100. The series resistance was set to 0.04 ohms.

1msec

width	Pmax	Voc	Jsc	FF
635	20.19438	0.666731	0.041391	0.731768
500	20.82746	0.673910	0.041269	0.748876
381	21.44406	0.681250	0.041153	0.764889
254	22.14189	0.690300	0.040913	0.783998
200	22.48175	0.694444	0.040768	0.794096
100	23.03756	0.703579	0.040158	0.815363

2 msec

width	Pmax	Voc	Jsc	FF
635	21.67701	0.680545	0.041421	0.768991
500	22.12940	0.685581	0.041277	0.781992
381	22.60176	0.690786	0.041158	0.794958
254	23.09343	0.697147	0.040917	0.809579
200	23.30028	0.700076	0.040771	0.816327
100	23.54203	0.706370	0.04016	0.829884

5 msec

width	Pmax	Voc	Jsc	FF
635	23.04518	0.688981	0.041444	0.807069
500	23.31351	0.692581	0.041282	0.815399
381	23.59155	0.696412	0.041161	0.823007
254	23.84200	0.701250	0.040919	0.830892
200	23.92451	0.703445	0.040773	0.834142
100	23.91677	0.708234	0.04016	0.840875

10 msec

width	Pmax	Voc	Jsc	FF
635	23.63857	0.691704	0.041451	0.824452
500	23.80777	0.694846	0.041284	0.829942
381	23.99374	0.698253	0.041162	0.834811
254	24.13276	0.702591	0.040919	0.839419
200	24.16118	0.704561	0.040773	0.841059
100	24.04268	0.708851	0.040161	0.844545

Table 7

Parameter of solar cells for a given lifetime when the width is varied.
These are 200 ohm-cm substrate cells.
With FSRV=100 and BSRV=500

1msec

width	Pmax	Voc	Jsc	FF
635	20.16947	0.6659	0.041392	0.731760
500	20.79719	0.672	0.041268	0.749932
381	21.40578	0.6795	0.041151	0.765528
254	22.10886	0.6875	0.040912	0.786036
200	22.42675	0.6919	0.040767	0.795086
100	22.94221	0.7	0.040157	0.816161

2msec

width	Pmax	Voc	Jsc	FF
635	21.62665	0.6792	0.041424	0.768669
500	22.07396	0.6832	0.041276	0.782771
381	22.53839	0.6888	0.041157	0.795034
254	23.00984	0.694	0.040915	0.810348
200	23.20442	0.6975	0.04077	0.815992
100	23.41238	0.70295	0.040158	0.829371

5msec

width	Pmax	Voc	Jsc	FF
635	22.95146	0.68749	0.041443	0.805550
500	23.21564	0.6906	0.041281	0.814336
381	23.47912	0.694	0.04116	0.821953
254	23.71412	0.698	0.040917	0.830324
200	23.78842	0.7005	0.040771	0.832925
100	23.77132	0.7045	0.040159	0.840213

10msec

width	Pmax	Voc	Jsc	FF
635	23.46774	0.687301	0.041450	0.823748
500	23.66851	0.691327	0.041284	0.829288
381	23.83332	0.694243	0.041162	0.834019
254	23.94701	0.697862	0.040919	0.838603
200	23.93319	0.699438	0.040773	0.839225
100	23.88770	0.7055	0.040159	0.843129

Table 8

Parameters of cell when the lifetime is specified but the width is variable. These cells are on 200 ohm-cm substrates with FSRV=500 and BSRV=500. The series resistance was set to 0.04 ohms.

1msec

width	Pmax	Voc	Jsc	FF
635	20.15460	0.663725	0.04138	0.733829
500	20.76913	0.670217	0.041267	0.750921
381	21.37980	0.676714	0.041152	0.767727
254	22.04006	0.684487	0.040911	0.787058
200	22.33842	0.688008	0.040767	0.796434
100	22.82040	0.695034	0.040156	0.817648

2 msec

width	Pmax	Voc	Jsc	FF
635	21.58986	0.676465	0.04142	0.770538
500	22.02379	0.680872	0.041276	0.783661
381	22.45238	0.685328	0.041157	0.796012
254	22.90945	0.690647	0.040915	0.810729
200	23.08745	0.692974	0.040769	0.817200
100	23.09533	0.697767	0.040158	0.824216

5 msec

width	Pmax	Voc	Jsc	FF
635	22.85116	0.684931	0.041442	0.805045
500	23.11209	0.687357	0.041281	0.814528
381	23.36109	0.690530	0.04116	0.821930
254	23.56834	0.694310	0.040917	0.829605
200	23.62900	0.695951	0.040771	0.832750
100	23.54331	0.699257	0.040158	0.838413

10 msec

width	Pmax	Voc	Jsc	FF
635	23.40666	0.686869	0.041449	0.822150
500	23.55626	0.689487	0.041282	0.827587
381	23.71569	0.692224	0.041161	0.832343
254	23.81800	0.695526	0.040918	0.836907
200	23.82934	0.696942	0.040772	0.838596
100	23.64601	0.699788	0.040159	0.841410

Table 9

Parameters of cell when the lifetime is specified but the width is variable. These cells are on 200 ohm-cm substrates with FSRV=500 and BSRV=500. The series resistance was set to 0.2 ohms.

5 msec

width	Pmax	Voc	Jsc	FF
635	22.6175	0.684302	0.041439	0.797604
500	22.85829	0.687355	0.041280	0.805596
381	23.12095	0.690533	0.04116	0.813478
254	23.33123	0.694307	0.040917	0.821262
200	23.39351	0.695957	0.040771	0.824444
100	23.31420	0.699259	0.040158	0.830251

10 msec

width	Pmax	Voc	Jsc	FF
635	23.14694	0.686873	0.041447	0.813062
500	23.31279	0.689485	0.041282	0.819036
381	23.47705	0.692192	0.041161	0.824006
254	23.57452	0.695523	0.040918	0.828355
200	23.59323	0.696944	0.040772	0.830285
100	23.41613	0.699787	0.040159	0.833232

Table 10

Parameter of solar cells for
a given lifetime when the width
is varied.
These are 15 ohm-sm substrate cells.
With FSRV=100 and BSRV=500

1msec

width	Pmax	Voc	Jsc	FF
635	20.75154	0.6651	0.041335	0.754823
500	21.16901	0.6719	0.041194	0.764825
381	21.63622	0.679	0.0411	0.775300
254	22.19789	0.6872	0.040884	0.790087
200	22.49652	0.691	0.040749	0.798951
100	22.94906	0.699	0.040151	0.817695

2msec

width	Pmax	Voc	Jsc	FF
635	21.86498	0.6771	0.041394	0.780115
500	22.22818	0.6824	0.041238	0.789891
381	22.62644	0.6872	0.041129	0.800543
254	23.04798	0.6935	0.0409	0.812574
200	23.22444	0.6965	0.040759	0.818089
100	23.39780	0.7021	0.040154	0.829941

5msec

width	Pmax	Voc	Jsc	FF
635	23.00395	0.6858	0.04143	0.809636
500	23.26041	0.68966	0.041264	0.817355
381	23.49760	0.693	0.041147	0.824047
254	23.71396	0.6975	0.04091	0.831056
200	23.78107	0.6998	0.040766	0.833603
100	23.74125	0.704	0.040156	0.839808

10msec No doping SRH effects.

width	Pmax	Voc	Jsc	FF
635	23.59667	0.68985	0.041443	0.825362
500	23.76376	0.6932	0.041273	0.830597
381	23.93400	0.6969	0.041154	0.834512
254	24.06660	0.7009	0.040913	0.839261
200	24.09277	0.7028	0.040768	0.840883
100	23.95623	0.7065	0.040157	0.844394

Table 11

Parameters of cell when the lifetime is specified but the width is variable. These cells are on 15 ohm-cm substrates with FSRV=500 and BSRV=500. The series resistance was set to 0.04 ohms

2 msec

width	Pmax	Voc	Jsc	FF
635	21.83029	0.675624	0.041393	0.780597
500	22.18505	0.680160	0.041237	0.790973
381	22.55592	0.684596	0.041129	0.801083
254	22.92539	0.689643	0.040899	0.812792
200	23.09655	0.692321	0.040759	0.818494
100	23.24456	0.696861	0.040153	0.830724

5 msec

width	Pmax	Voc	Jsc	FF
635	22.93968	0.683247	0.041429	0.810410
500	23.16258	0.686485	0.041263	0.817701
381	23.38590	0.689667	0.041147	0.824093
254	23.54287	0.693245	0.040909	0.830144
200	23.61178	0.695263	0.040765	0.833089
100	23.52184	0.698426	0.040155	0.838708

10 msec

width	Pmax	Voc	Jsc	FF
635	23.48539	0.686822	0.041442	0.825110
500	23.63527	0.689762	0.041273	0.830223
381	23.75644	0.692675	0.041153	0.833393
254	23.85034	0.695950	0.040913	0.837635
200	23.89203	0.697840	0.040768	0.839802
100	23.70122	0.700836	0.040156	0.842177

Table 12

Parameters of cell when the lifetime is specified but the width is variable. These cells are on 15 ohm-cm substrates with FSRV=500 and BSRV=500. The series resistance was set to 0.2 ohms.

2 msec

width	Pmax	Voc	Jsc	FF
635	21.59438	0.675624	0.041393	0.772162
500	21.9494	0.680163	0.041237	0.782568
381	22.31969	0.684595	0.041129	0.792695
254	22.70751	0.689638	0.040899	0.805072
200	22.85795	0.692324	0.040759	0.810035
100	23.01592	0.696866	0.040153	0.822547

5 msec

width	Pmax	Voc	Jsc	FF
635	22.69777	0.683253	0.041429	0.801857
500	22.92022	0.686485	0.041263	0.809145
381	23.14428	0.689670	0.041146	0.815584
254	23.29942	0.693245	0.040909	0.821559
200	23.36877	0.695267	0.040765	0.824510
100	23.29301	0.698432	0.040155	0.830542

10 msec

width	Pmax	Voc	Jsc	FF
635	23.23839	0.686818	0.041442	0.816439
500	23.38973	0.689764	0.041273	0.821595
381	23.54218	0.692671	0.041153	0.825882
254	23.60461	0.695950	0.040913	0.829004
200	23.63468	0.697875	0.040768	0.830715
100	23.47213	0.700822	0.040156	0.834053

Table 13

Comparison of 5 msec 15 ohm-cm material with and without doping effects

5 msec with doping

width	Pmax	Voc	Jsc	FF
635	23.00395	0.6858	0.04143	0.809636
500	23.26041	0.68966	0.041264	0.817355
381	23.49760	0.693	0.041147	0.824047
254	23.71396	0.6975	0.04091	0.831056
200	23.78107	0.6998	0.040766	0.833603
100	23.74125	0.704	0.040156	0.839808

5 msec no doping

width	Pmax	Voc	Jsc	FF
635	23.04601	0.6869	0.04143	0.809817
500	23.31057	0.6905	0.041265	0.818102
381	23.562	0.695	0.041148	0.823907
254	23.79582	0.6997	0.04091	0.831303
200	23.87095	0.7011	0.040766	0.835202
100	23.83725	0.7062	0.040156	0.840578

In the 15 ohm-cm material with a 10 msec lifetime an assumption had to be made to obtain convergence. The SRH lifetime model used in PC-1D is for a trap located at mid-gap and as a function of doping density. In order to obtain the 10 msec minority carrier lifetime in the base, the doping dependence of the SRH model had to be eliminated. This leads to slightly higher lifetimes in the emitter and buffer, and in turn raises the efficiency. This trend was verified by plotting a comparison of 5 msec lifetime data with and without doping density effects, Figure 10. Figure 11 shows the efficiency of 15 ohm-cm cells with a series resistance of 0.2 ohms, and bulk lifetimes of 2, 5, and 10 msec. The maximum efficiency is obtained for a cell thickness of 200 microns for the higher lifetime (10 msec) material. For 2 msec lifetime material it appears that the maximum efficiency would be in cells which are 100 microns or thinner. The same trend is observed for cells with a lower series resistance (0.04 ohms instead of 0.2 ohms), Figure 12, and a better passivated surface (FSRV=100 cm/sec instead of 500 cm/sec), Figure 13. Figures 12 and 13 also show that the cell design in Table 5 with 15 ohm-cm base and 10 msec lifetime can produce cell efficiencies above 24% provided the FSRV is 100 cm/sec, BSRV is 500 cm/sec, and Rs is 0.04 ohms. Figure 14 shows that if the 10 msec lifetime cannot be maintained during processing then the cell should be thinned and passivated to obtain the same efficiency. As expected, the open circuit voltage does not change with the change in the series resistance but it changes significantly when the front surface is passivated due to the decrease in reverse current, Figure 15. The short circuit current shows no appreciable change with either a change in series resistance or surface passivation values used in these calculations, Figure 16. The fill factor appears to be the parameter that is the most sensitive to fluctuations in the series resistance and surface passivation. Figure 17 shows that as the series resistance

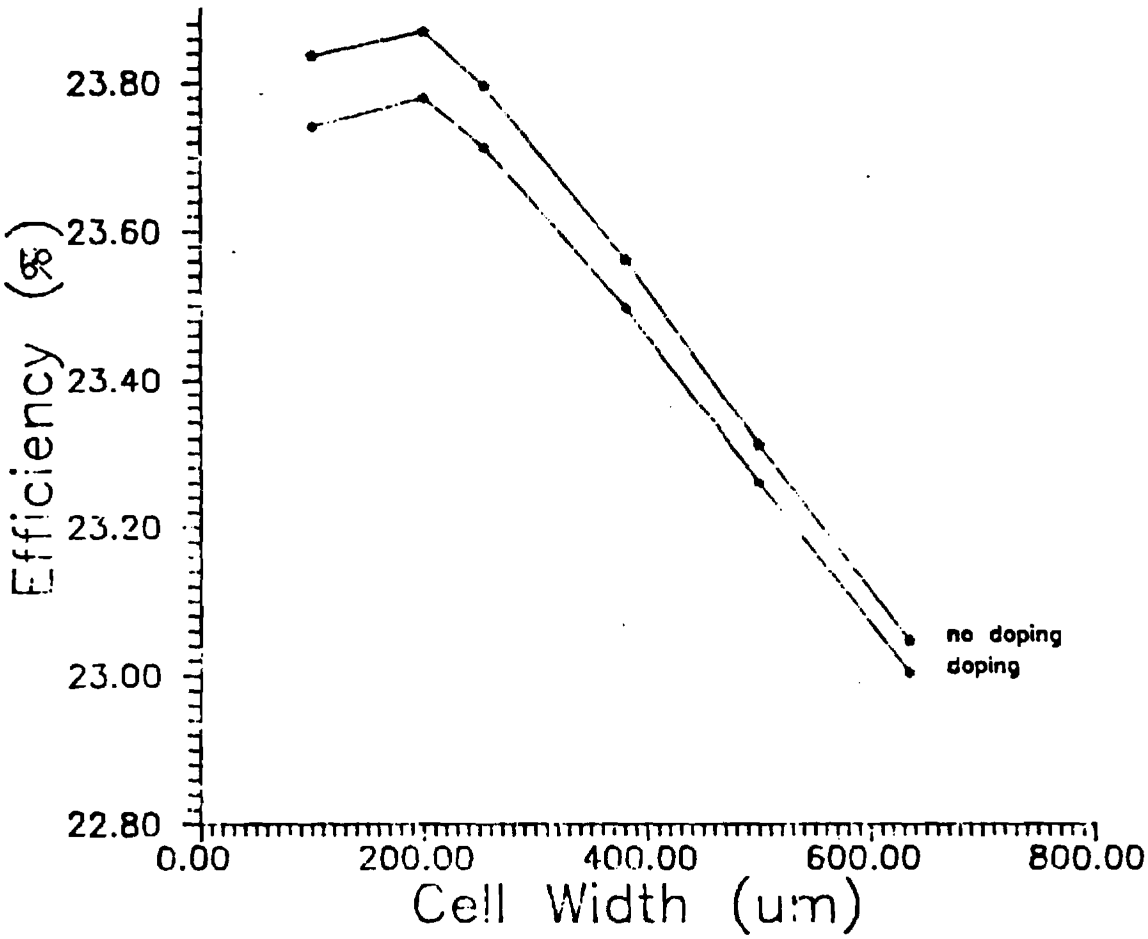


Figure 10. Comparison of 5 msec lifetime 15 ohm–cm material with and without doping effects included in the SRH lifetime model.

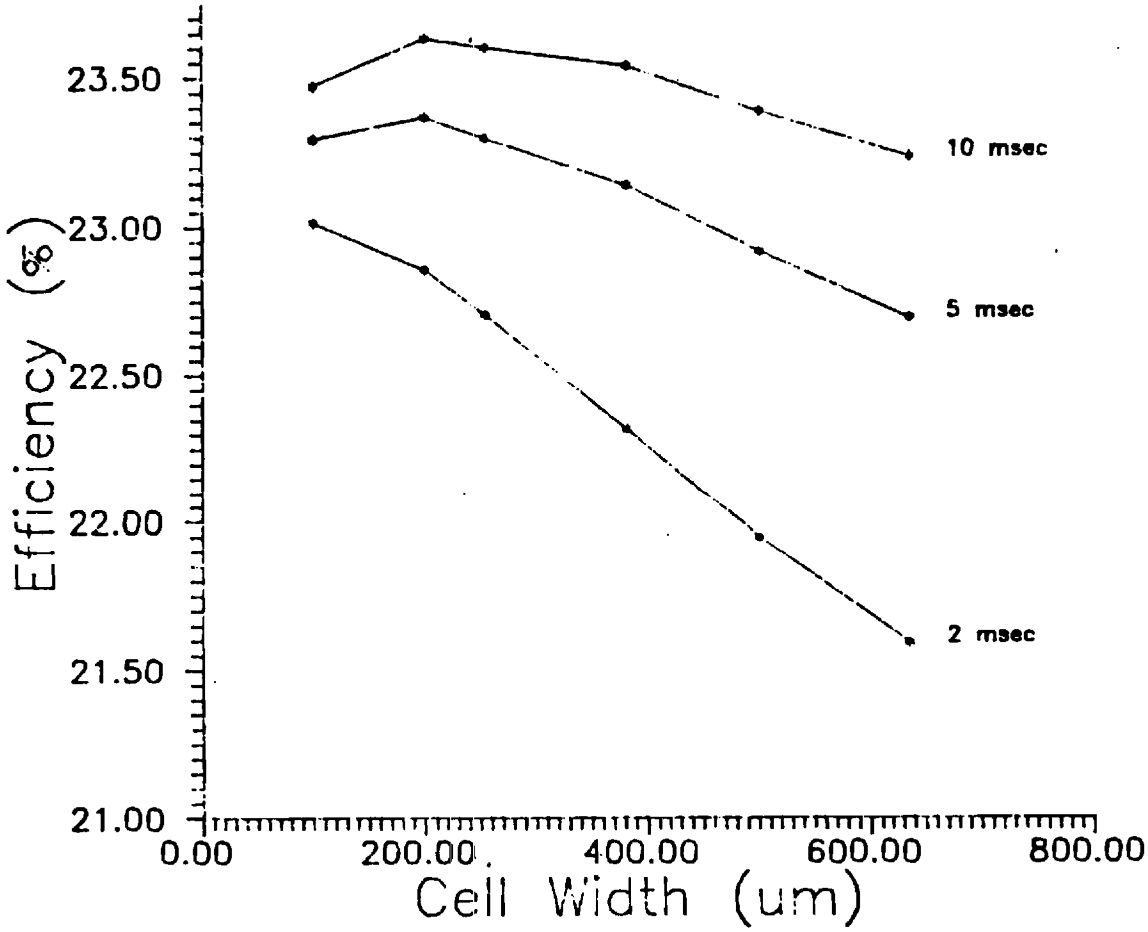


Figure 11. Efficiency as a function of cell width for 15 ohm--cm material with a series resistance of 0.2 ohms and FSRV and BSRV of 500 cm/sec.

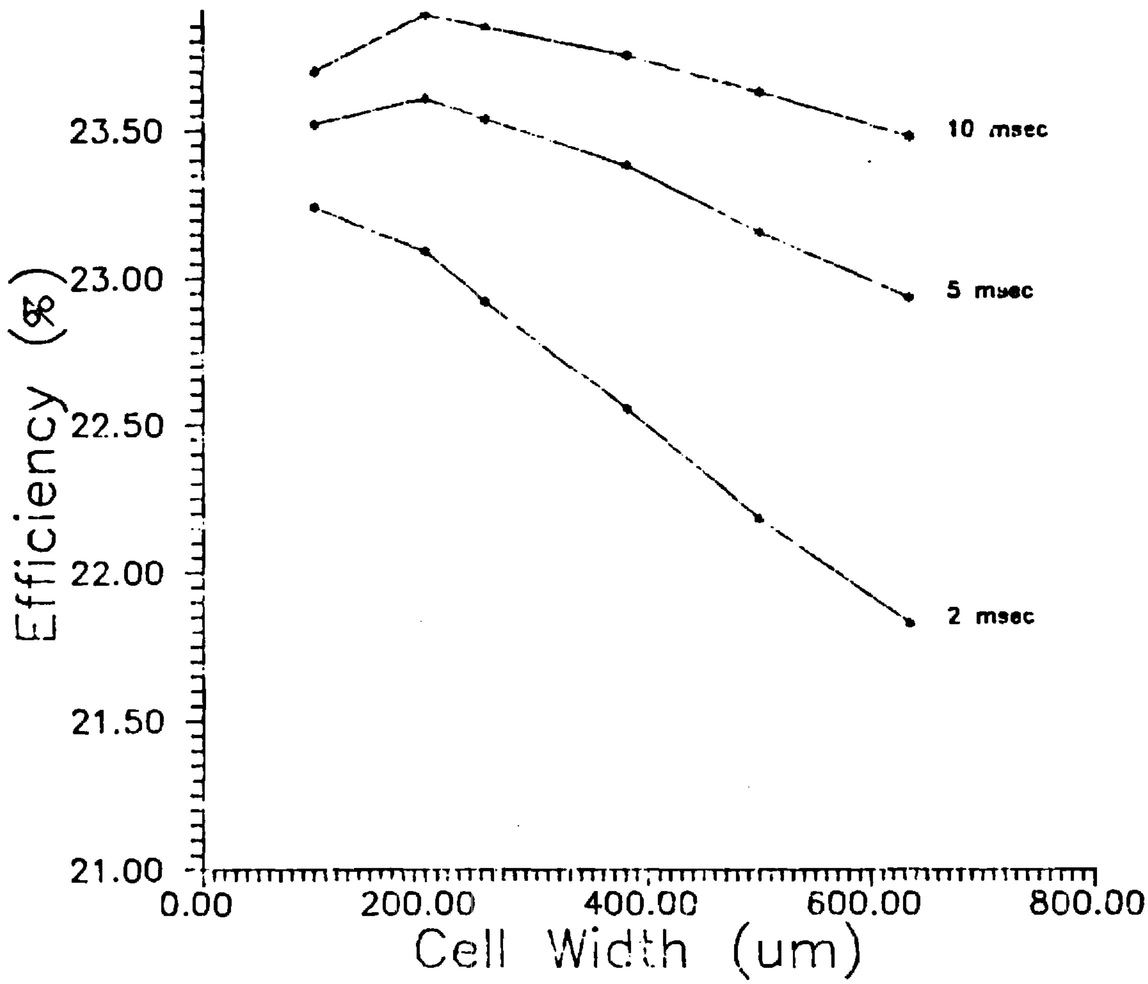


Figure 12. Efficiency as a function of cell width for 15 ohm–cm material with a series resistance of 0.04 ohms and FSRV and BSRV of 500 cm/sec.

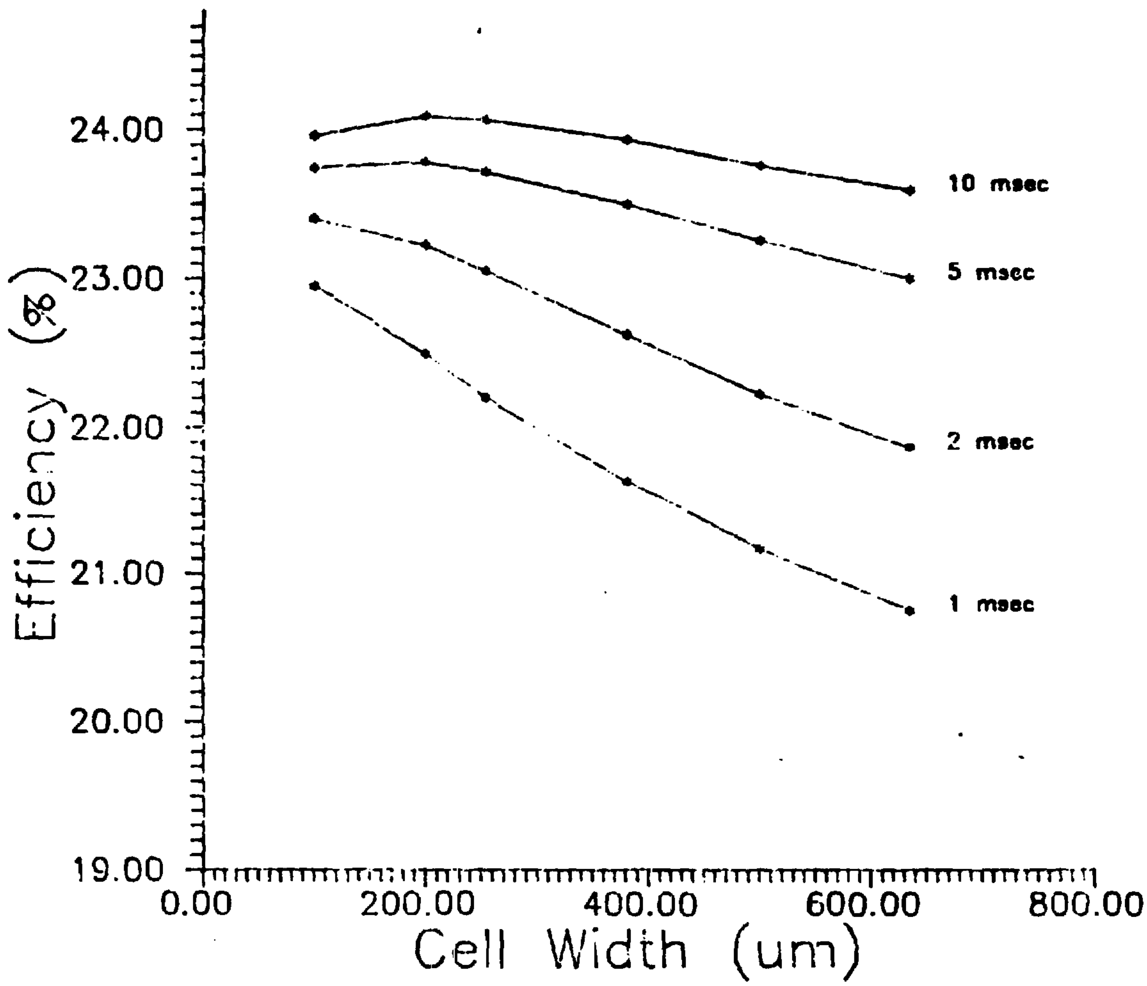


Figure 13. Efficiency as a function of cell width for 15 ohm−cm material with a series resistance of 0.04 ohms and FSRV of 100 cm/sec and BSRV of 500 cm/sec.

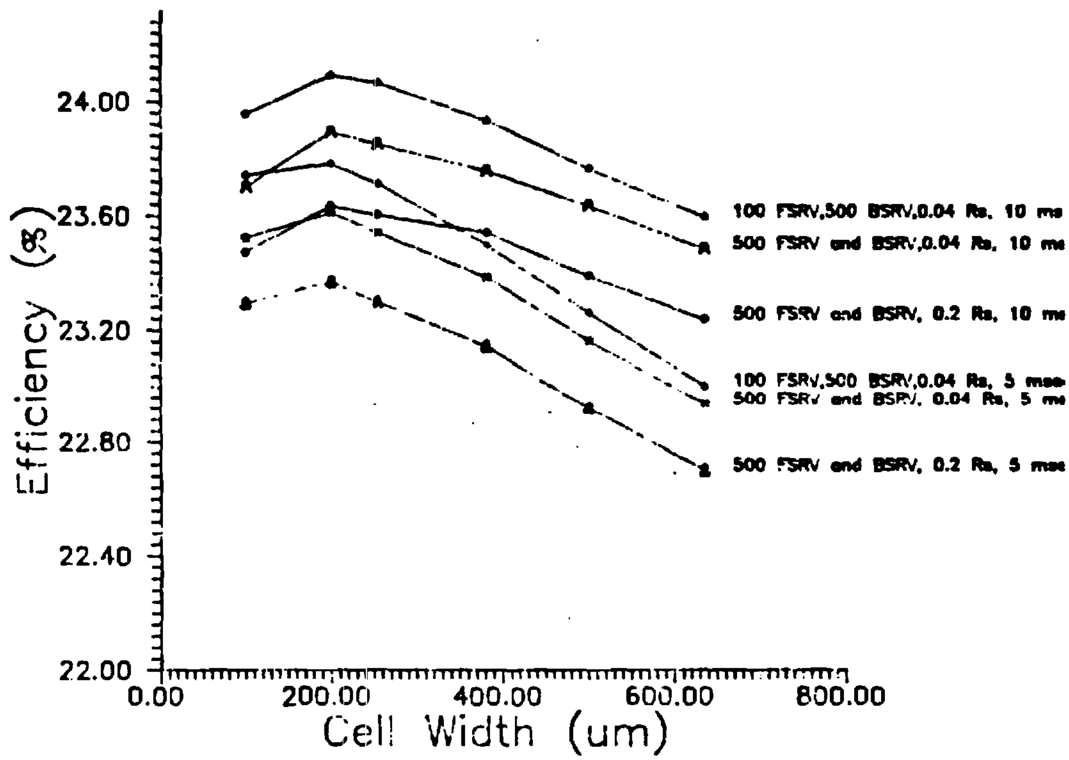


Figure 14. Efficiency as a function of cell width for 15 ohm–cm material with variable series resistance, FSRV, and BSRV for 5 and 10 msec lifetime material.

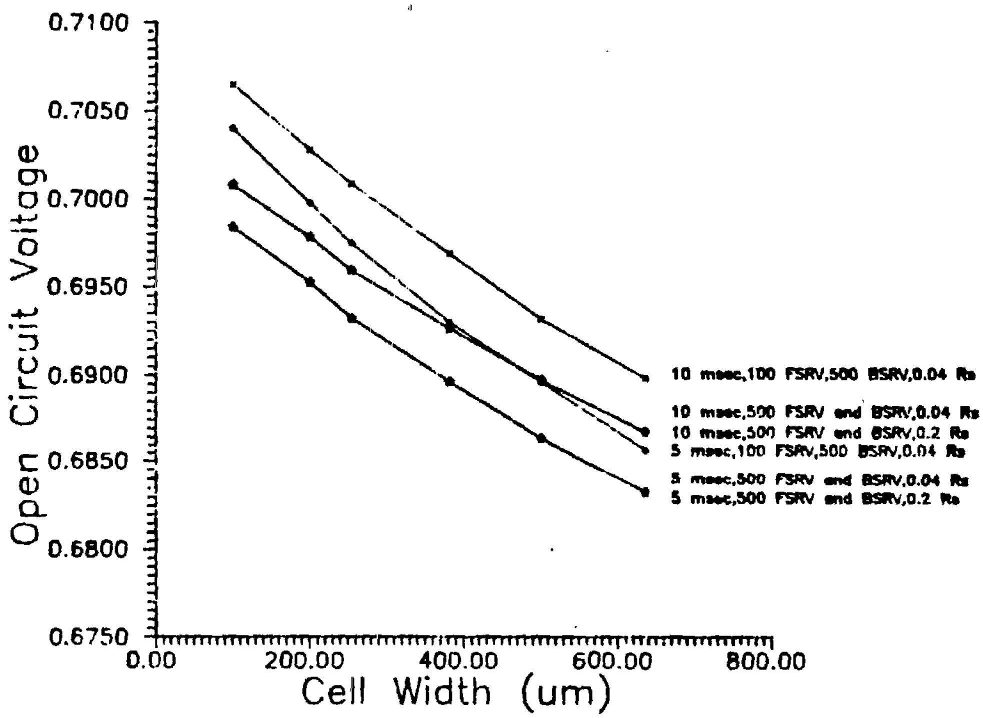


Figure 15. Open circuit volotge as a function of cell width for 15 ohm-cm material with variable series resistance, FSRV, and BSRV using 5 and 10 msec lifetimes.

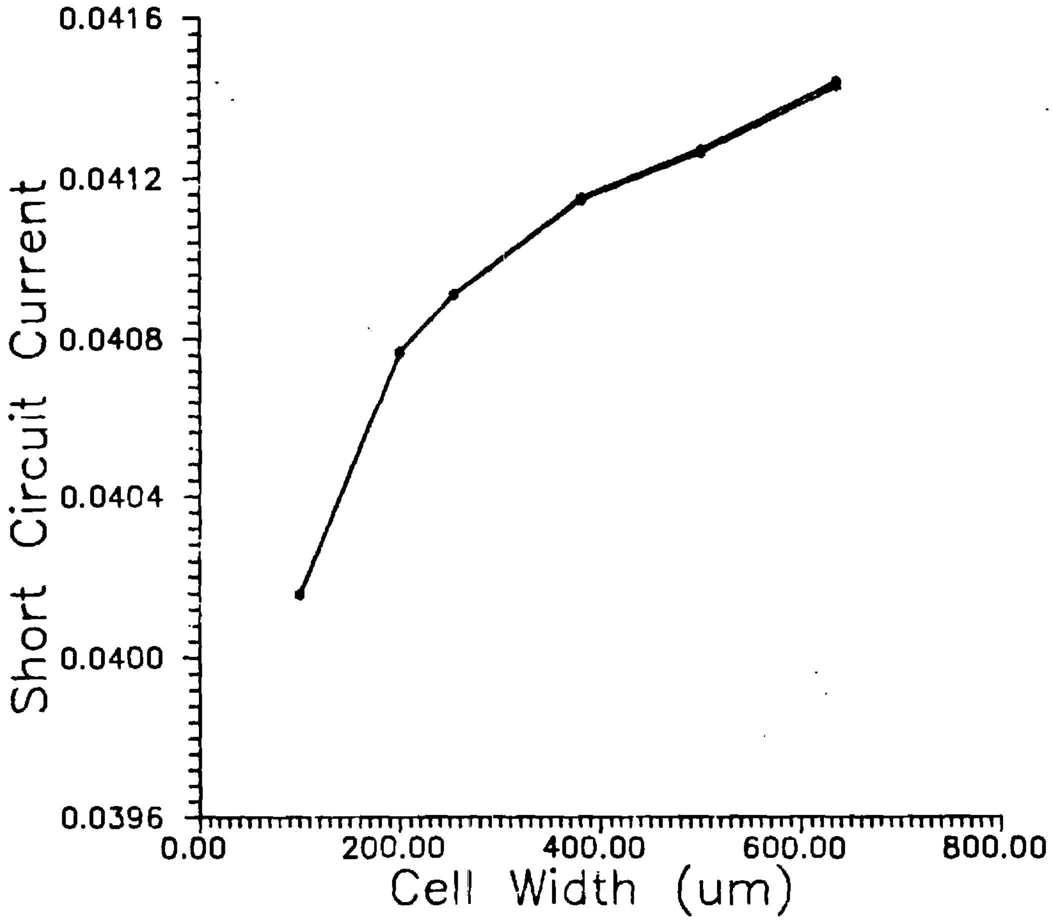


Figure 16. Short circuit current as a function of cell width for 15 ohm–cm material with variable series resistance, FSRV, and BSRV using 5 and 10 msec lifetimes.

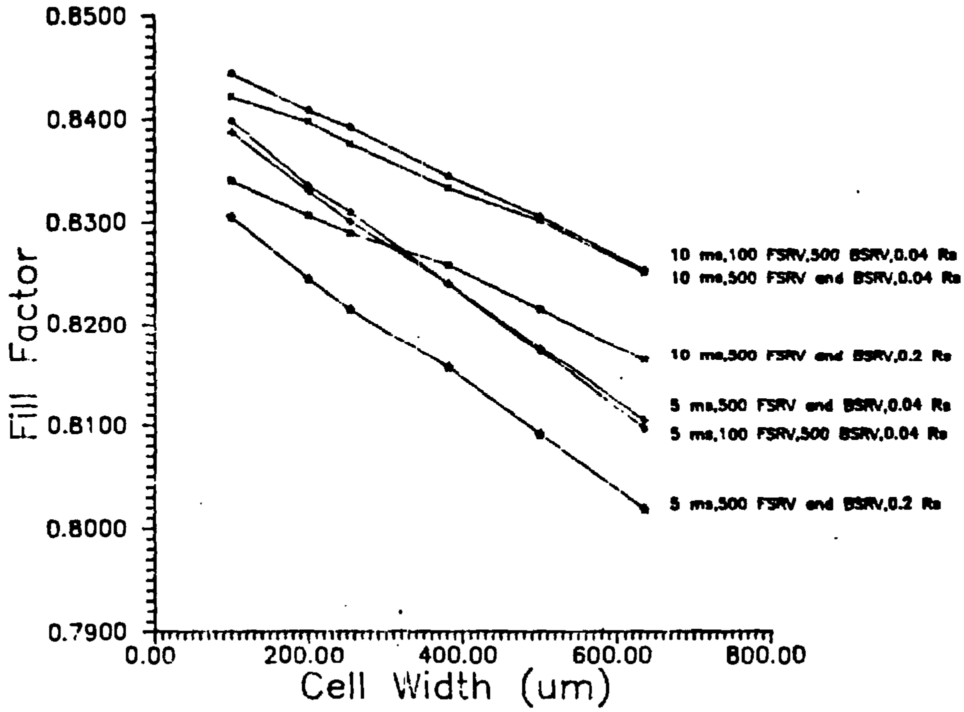


Figure 17. Fill Facotr as a function of cell width for 15 ohm–cm material with variable series resistance, FSRV, and BSRV for 5 and 10 msec lifetime material.

is increased the fill factor decreases. Changing the front surface passivation produces a smaller change in the fill factor as the cell is thinned.

Model calculations were also performed for 200 ohm-cm high lifetime silicon. The basic cell design features are listed in Table 5. In comparison to the 15 ohm-cm material, the 200 ohm-cm base cells suffer more from poor passivation and higher series resistance, Figures 18 and 19. As the series resistance is reduced to 0.04 ohms the cells approach the same efficiencies in both 15 ohm-cm and 200 ohm-cm cells. Notice that 200 microns thick cells with FSRV and BSRV of 100 cm/sec with a bulk lifetime of 10 msec can produce cell efficiciency in excess of 24% with the cell design in Table 5. Figure 20 also confirms the same idea that the efficiency is comparable in the two materials for FSRV and BSRV of 500 cm/sec, except the maximum efficiency is less than 24%. This remains true until the cell reaches a thickness at which the series resistance in the 200 ohm-cm cell starts to dictate the performance. Remember that the 10 msec lifetime values for the 200 ohm-cm cells do include the doping dependence of the SRH lifetime while the 15 ohm-cm cells do not, partially explaining the discrepancy in the 10 msec lifetime values. In 200 ohm-cm material with 10 msec lifetime, Figure 21, and equal front and back surface recombination velocities, the efficiency curves as a function of cell thickness are of the same general form, independent of the series resistance in the range of 0.04 to 0.2 ohms. Yet from the middle two curves it can be seen that improved passivation of the front surface leads to a higher efficiency. This appears to be especially true as the cell is thinned. Figure 22 shows the general trend for the open circuit voltages that were simulated using 200 ohm-cm material. As the cell is thinned the cell efficiency and the open circuit voltage begins to rise, but if the cell is thinned far enough (100 microns) the cell efficiency or

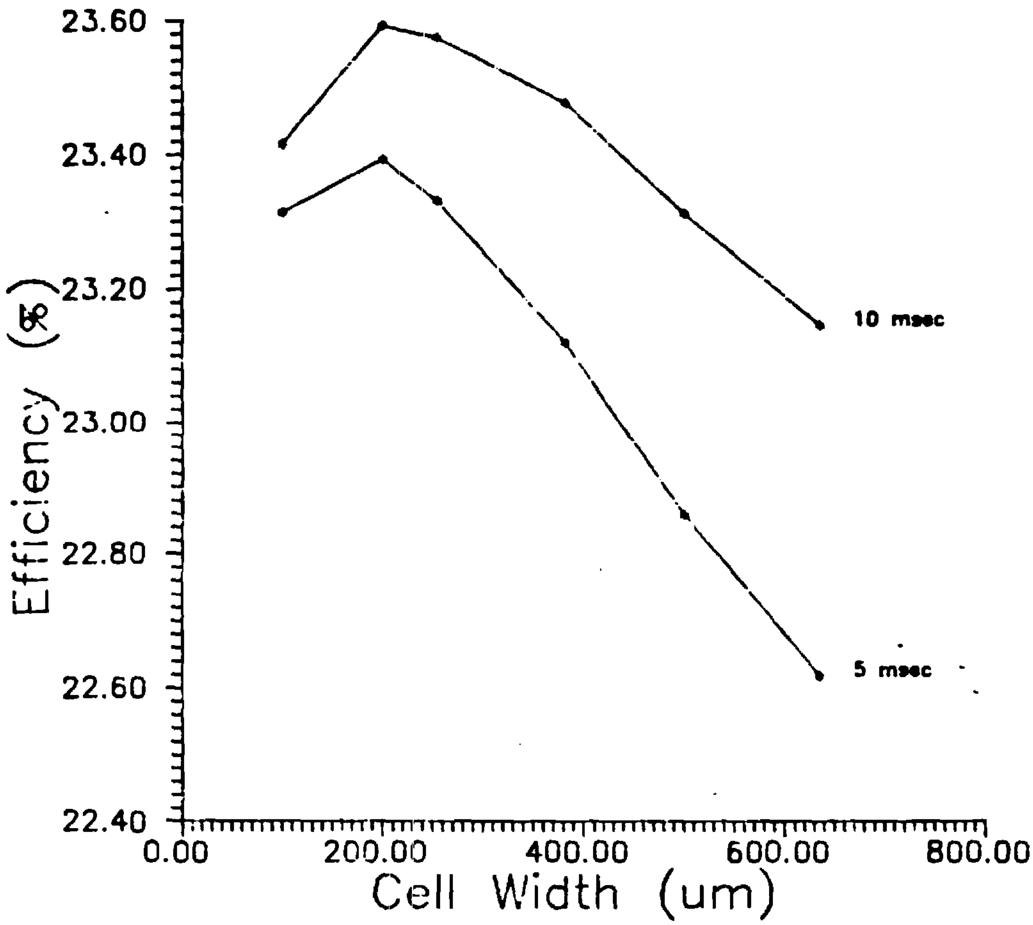


Figure 18. Efficiency as a function of cell width for 200 ohm–cm material with series resistance of 0.2 ohms and FSRV and BSRV of 500 cm/sec.

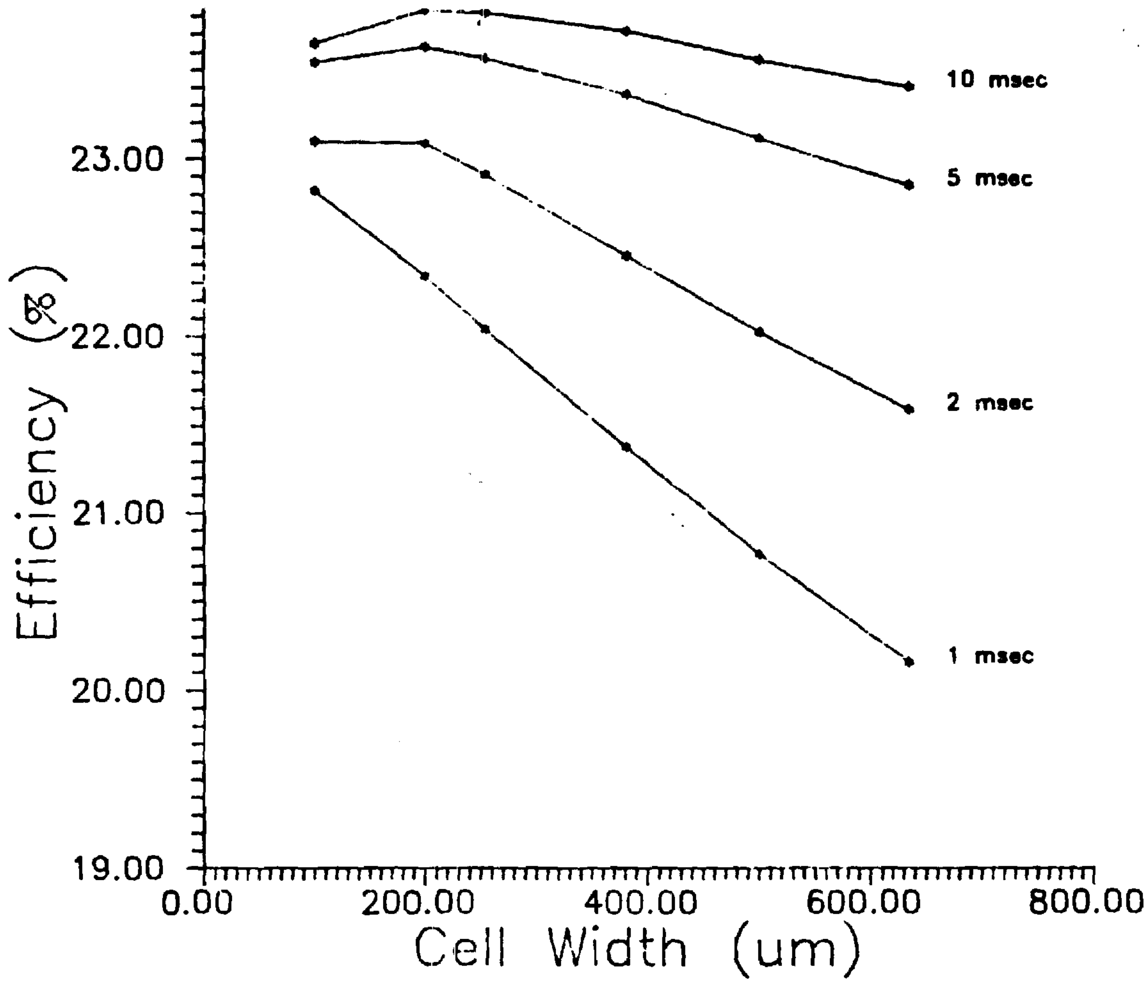


Figure 19. Efficiency as a function of cell width for 200 ohm–cm material with series resistance of 0.04 ohms and FSRV and BSRV of 500 cm/sec.

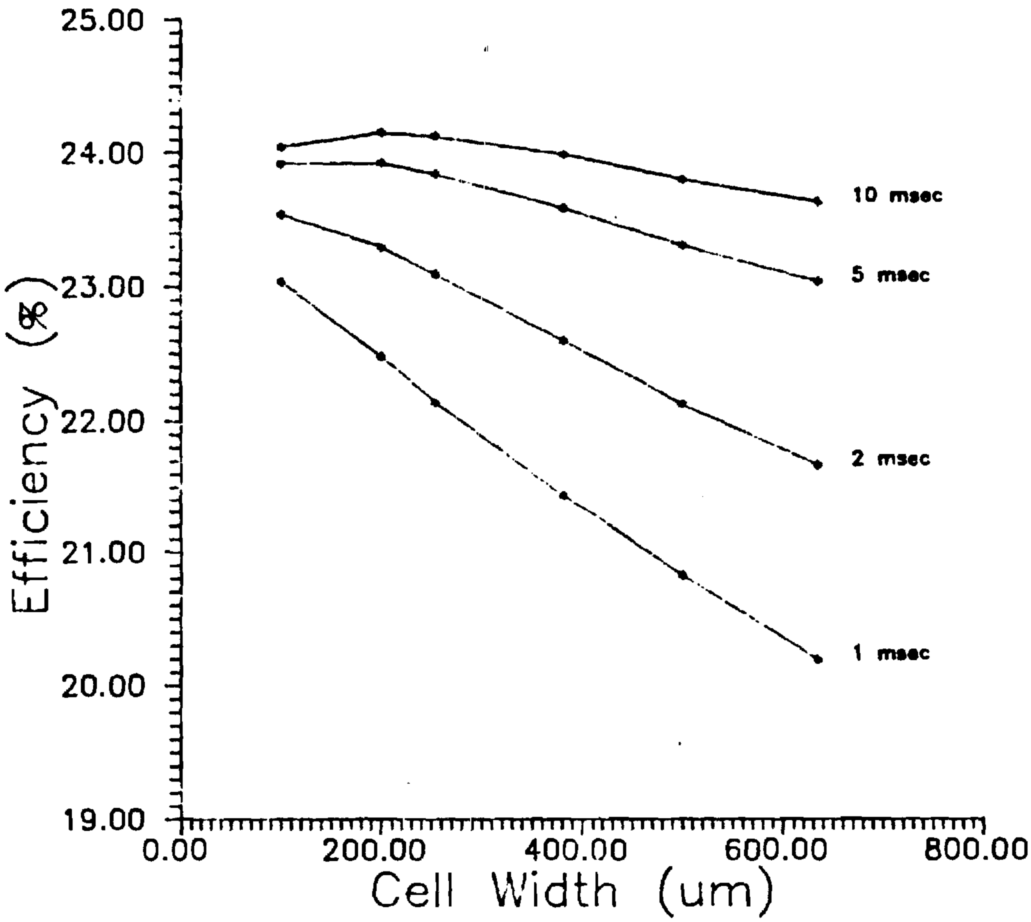


Figure 20. Efficiency as a function of cell width for 200 ohm–cm material with series resistance of 0.04 ohms and FSRV and BSRV of 100 cm/sec.

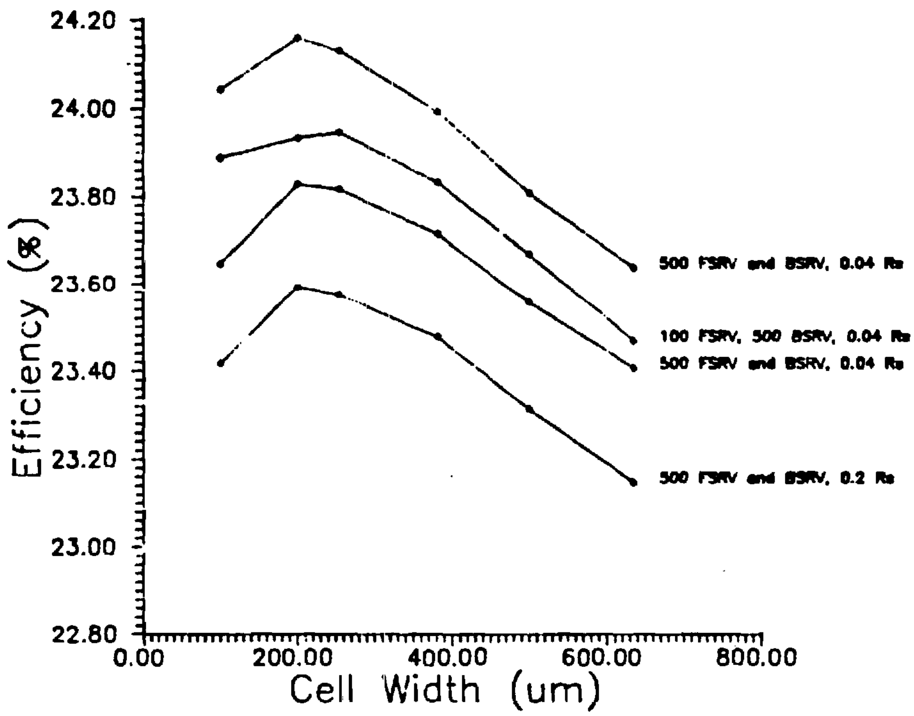


Figure 21. Efficiency as a function of cell width for 200 ohm−cm material with variable series resistance, FSRV, and BSRV with a lifetime of 10 msec.

as a function of cell thickness are of the same general form, independent of the series resistance in the range of 0.04 to 0.2 ohms. Yet from the middle two curves it can be seen that passivating the front surface leads to a higher efficiency. This appears to be especially true as the cell is thinned. The front surface can have more of an impact upon the performance of these high efficiency cells. Figure 22 shows the general trend for some of the open circuit voltages that were simulated using 200 ohm-cm material. As the cell is thinned the cell efficiency and the open circuit voltage begins to rise, but if the cell is thinned far enough (100 microns) the cell efficiency or the Voc tend to converge for all lifetimes in the range of 1-10 msec. Figures 23 and 24 show that for these high lifetime high efficiency cells, the short circuit current is not only lifetime independent, but also independent of the series resistance and the surface passivation in the range of 100-500 cm/sec. This should not be taken as a general statement since only a limited range of conditions that have produced very high cell efficiencies have been simulated. The short circuit current tends to decrease as the cell is thinned because the reduced absorption of the long wavelength photons. The fill factor follows the general trend of the open circuit voltage, which increases as the cell is thinned due to reduced bulk recombination. Figure 25 is a typical representation of the fill factor experienced for these simulations. The fill factor changes appreciably with changes in the series resistance and the passivation as shown in figure 26, which is to be expected.

Figures 27 through 30 are comparisons of parameters using the two different resistivities. As observed in figure 27 the 15 ohm-cm material exhibits higher efficiencies when using thicker cells. When the cell is thinned to about 250-300 microns, the 200 ohm-cm cells overtake the 15 ohm-cm and show better efficiencies. Figure 28 shows that only for

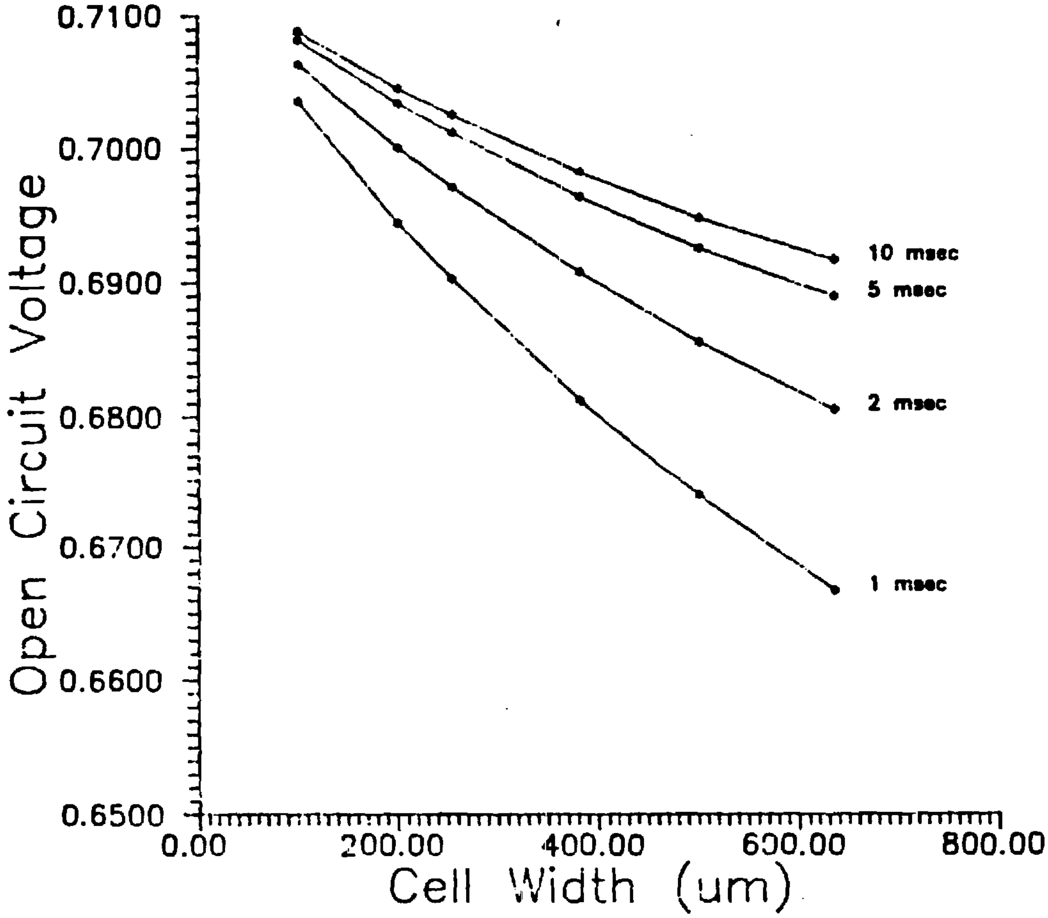


Figure 22. Open Circuit Voltage as a function of cell width for 200 ohm–cm material with FSRV and BSRV of 100 cm/sec and series resistance of 0.04 ohms

for all lifetimes in the range of 1-10 msec. Figures 23 and 24 show that for these high lifetime high efficiency cells, the short circuit current is not only lifetime independent, but also independent of the series resistance and the surface passivation in the range of 100-500 cm/sec. This should not be taken as a general statement since only a limited range of conditions that have produced very high cell efficiencies have been simulated. The short circuit current tends to decrease as the cell is thinned because of the reduced absorption of the long wavelength photons. The fill factor follows the general trend of the open circuit voltage, which increases as the cell is thinned due to reduced bulk recombination. Figure 25 is a typical representation of the fill factor experienced for these simulations which changes appreciably with the series resistance and the passivation as shown in Figure 26.

Figures 27 through 30 are comparisons of parameters using the two different resistivities. As observed in figure 27, the 15 ohm-cm material exhibits higher efficiencies when using thicker cells. When the cell is thinned to about 250-300 microns, the 200 ohm-cm cells overtake the 15 ohm-cm and show better efficiencies. Figure 28 shows that only for low series resistance and heavily passivated cells is the open circuit voltage appreciably different for the two resistivities. Examining figure 29 leads to the conclusion that series resistance and passivation have little effect on the short circuit current. Figure 30 shows that the fill factor is pretty much constant for the same condition in both the 200 ohm-cm and 15 ohm-cm cells. Finally, cell efficiencies in excess of 24% can be realized on both 15 and 200 ohm-cm silicon material provided the carrier lifetime is about 10 msec and the cell thickness is approximately 200 microns.

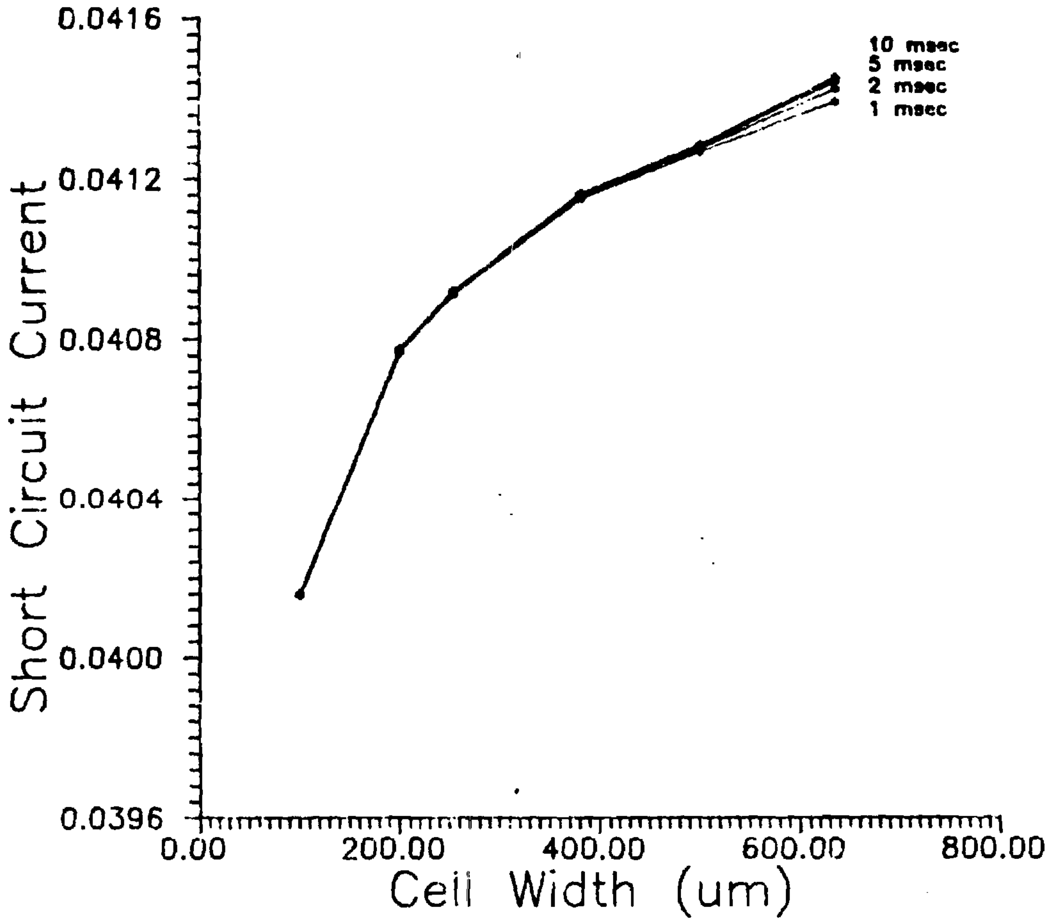


Figure 23. Short circuit current as a function of cell width for 200 ohm−cm material with FSRV of 100 cm/sec, BSRV of 500 cm/sec, and series resistance of 0.04 ohms.

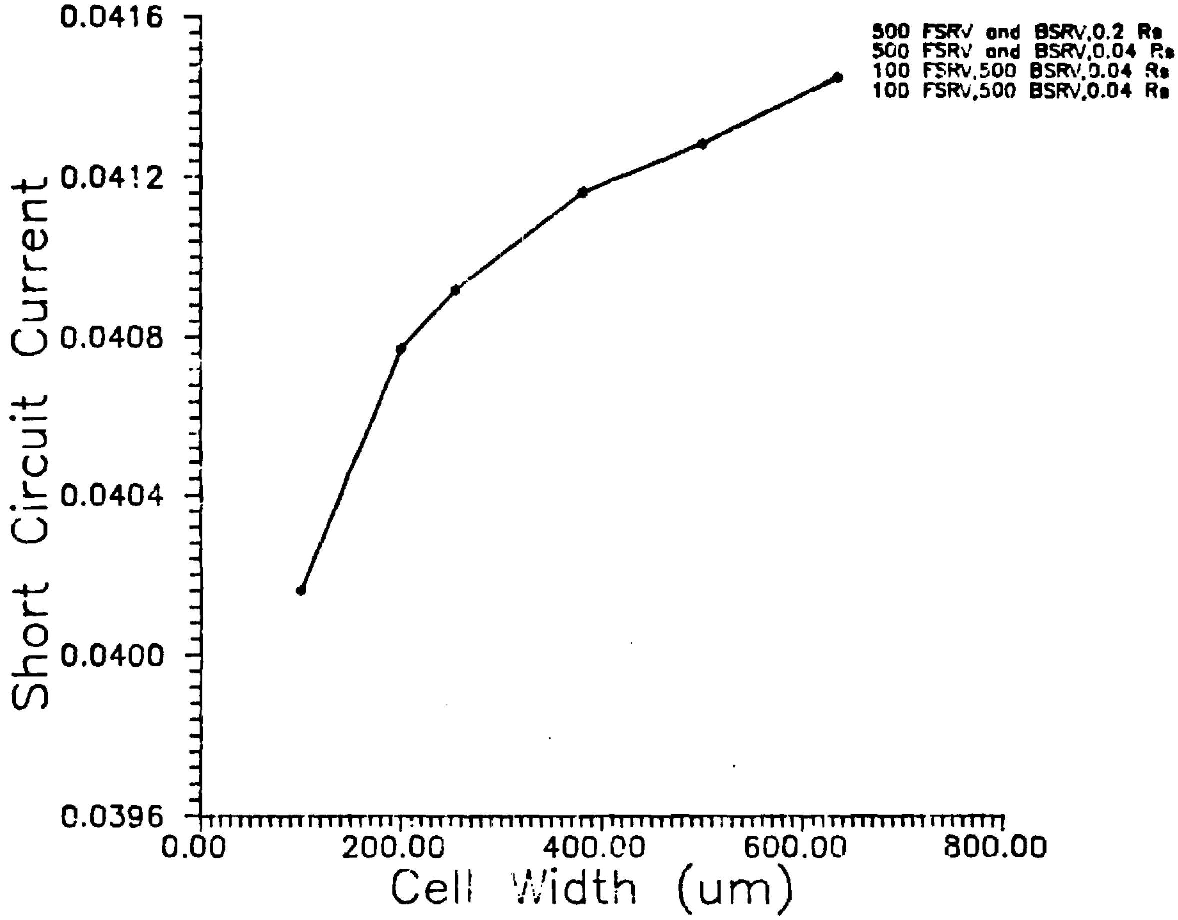


Figure 24. Short circuit current as a function of cell width for 200 ohm-cm material a lifetime of 10 msec and variable FSRV, BSRV, and series resistance.

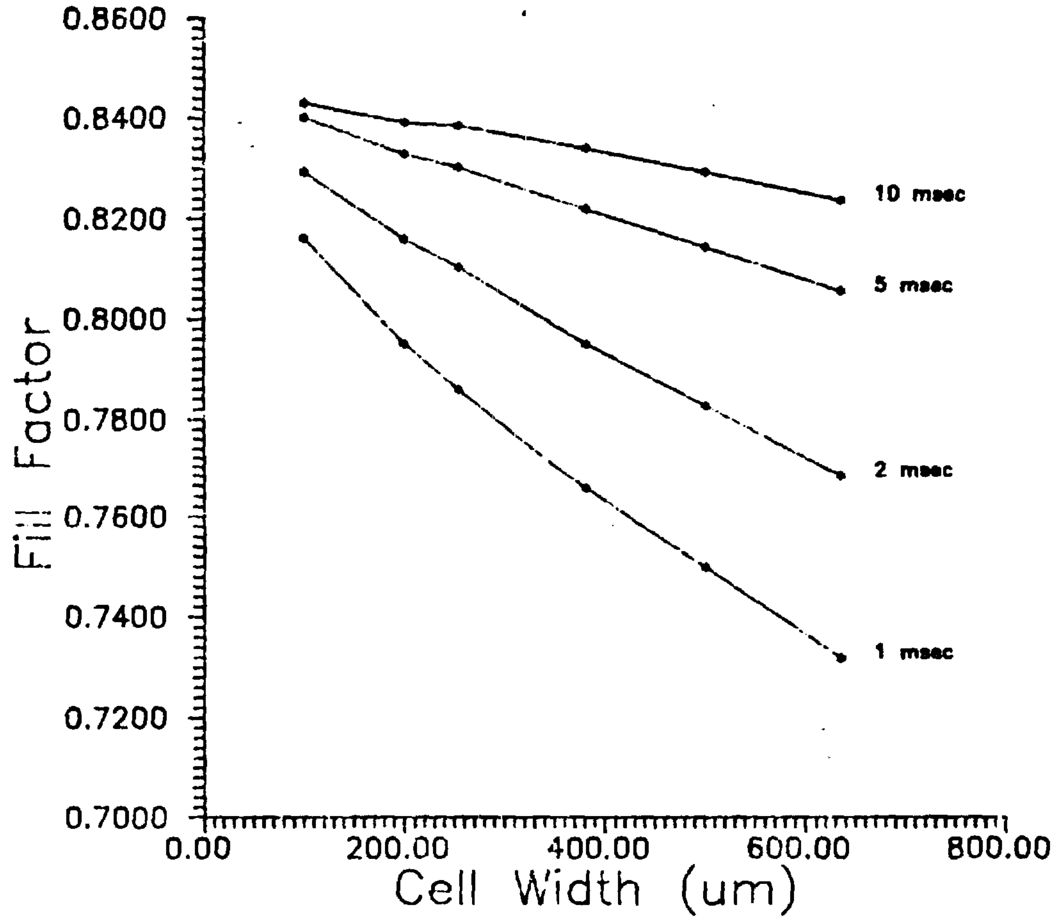


Figure 25. Fill Factor as a function of cell width for 200 ohm−cm material with a series resistance of 0.04 ohms and FSRV of 100 cm/sec and BSRV of 500 cm/sec

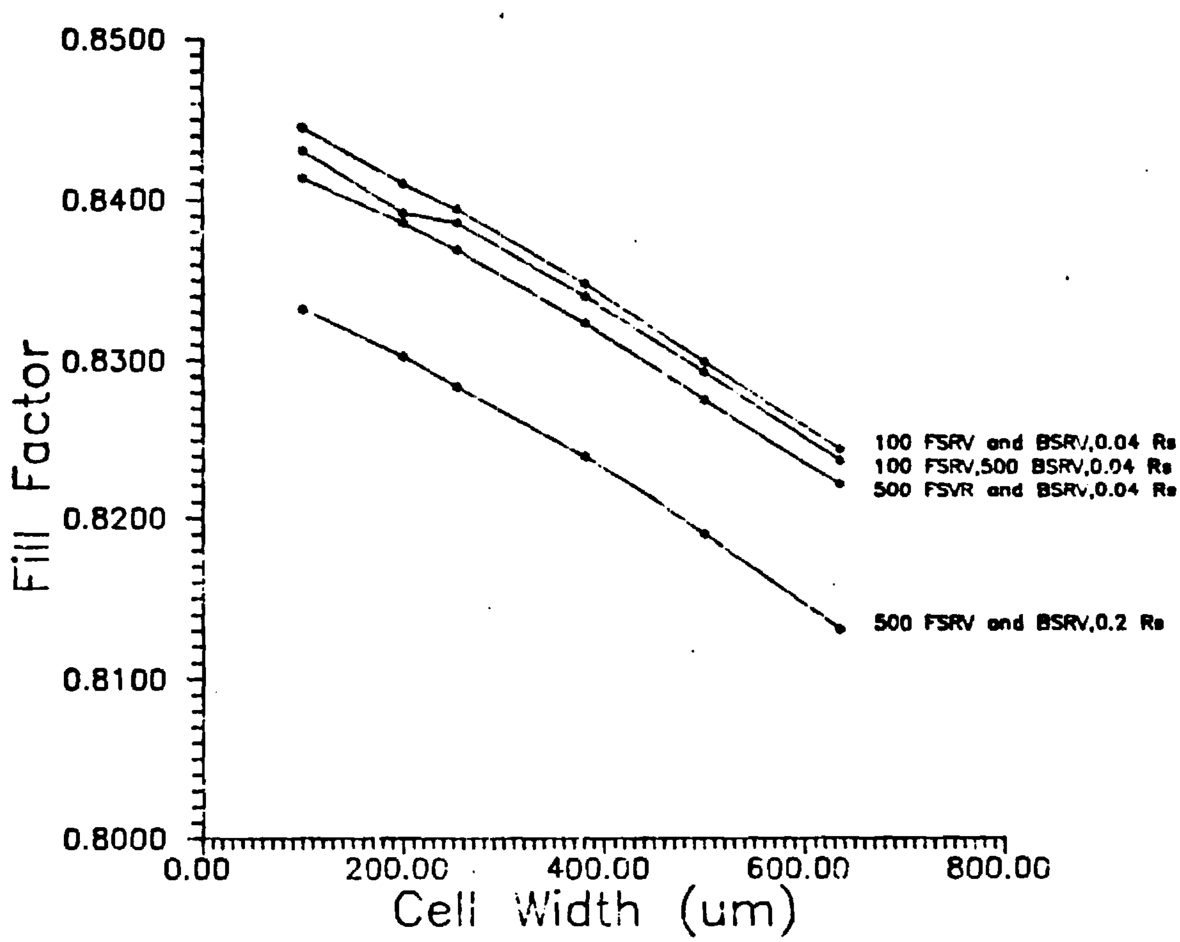


Figure 26. Fill Factor as a function of cell width for 200 ohm-cm material with a lifetime of 10 msec and variable series resistance, FSRV, and BSRV.

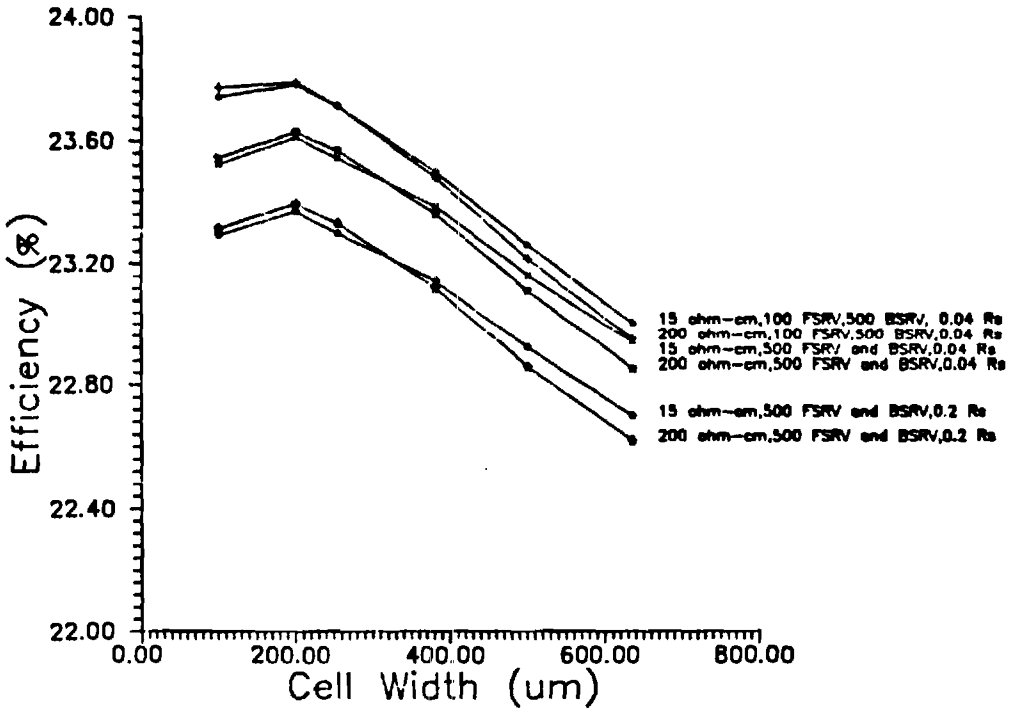


Figure 27. Efficiency as a function of cell width for 5 msec lifetime material with variable resistivity base, series resistance, FSRV, and BSRV.

low series resistance and heavily passivated cells is the open circuit voltage appreciably different for the two resistivities. Examining figure 29 leads to the conclusion that series resistance and passivation have little effect on the short circuit current. Figure 30 shows that the fill factor is pretty much constant for the same condition in both the 200 ohm-cm and 15 ohm-cm cells. Finally, cell efficiencies in excess of 24% can be realized on both 15 and 200 ohm-cm silicon material provided the carrier lifetime is about 10 msec and the cell thickness is approximately 200 microns.

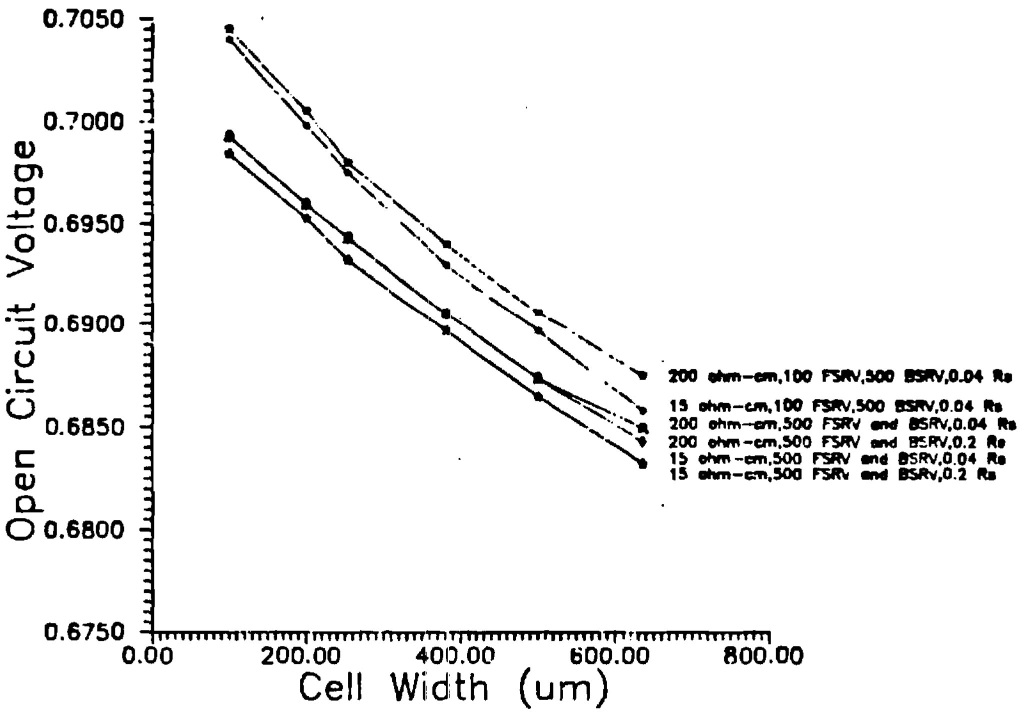


Figure 28. Open circuit voltage as a function of cell width for 5 msec material with variable base resistivity, series resistance, FSRV, and BSRV.

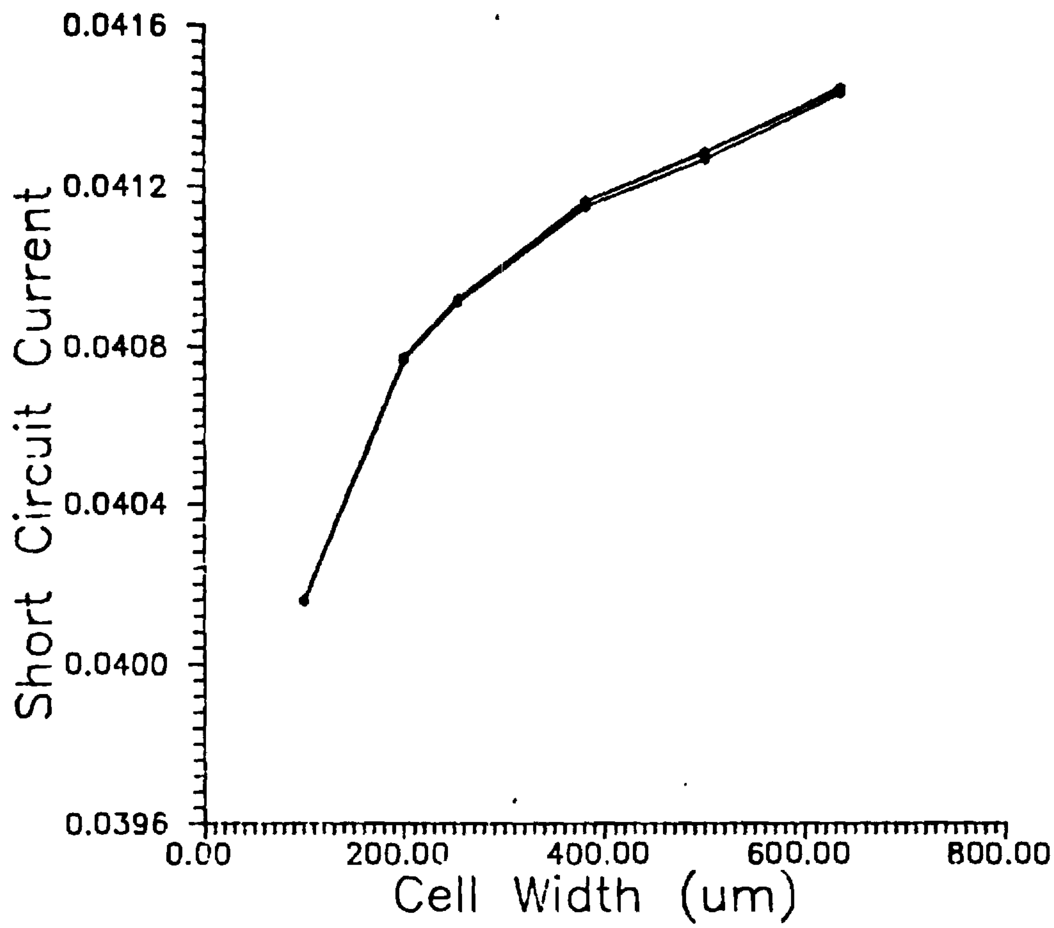


Figure 29. Short circuit current as a function of cell width for 5 msec material with variable base resistivity, series resistance, FSRV, and BSRV. The same cells as fig. 28.

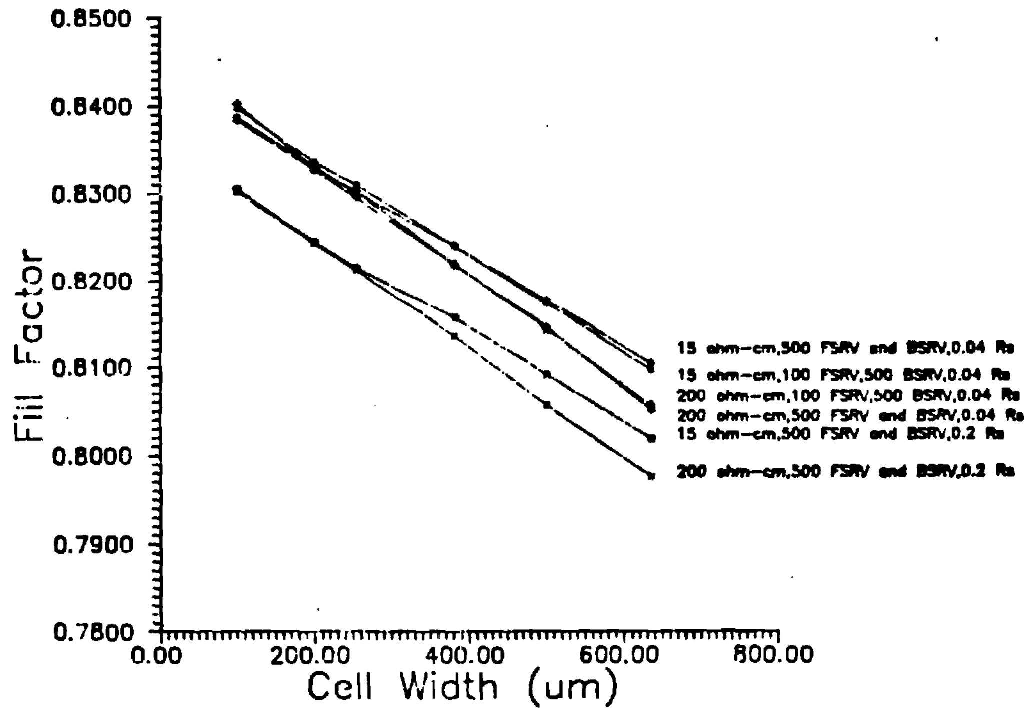


Figure 30. Fill factor as a function of the cell width for 5 msec material with variable base resistivity, series resistance, FSRV, and BSRV.

2.2 DLTS Measurements and Analysis of Ion-Implanted and Annealed Samples from Spire

2.2 (a) DLTS Analysis of Low Resistivity Samples from Spire

We performed the model calculations using diffusion length in the range of 150-300μm, which is typical of high efficiency solar cells fabricated on low resistivity float zone silicon. Spire cells generally show diffusion length in the range of 150-200μm but the diffused cells fabricated on similar material by Green(4) and Rohatgi(5) have shown diffusion lengths in the range of 220-300μm. DLTS measurements on selected samples were performed to find out why Spire cells have low diffusion length. Improved diffusion length in the Spire cells to a value of 300 μm alone can increase the cell efficiency from 18-19% to 19-20% range.

Table 14 shows a description of samples supplied by Spire, along with the measured diffusion length on each sample. Each sample had small dot-size electrode to perform the DLTS measurements. Samples with implanted junctions had ohmic dot-contacts to perform DLTS measurements. Ti-Ag Schottky dots were deposited for the DLTS measurements on those samples which did not have any junction at the end of processing.

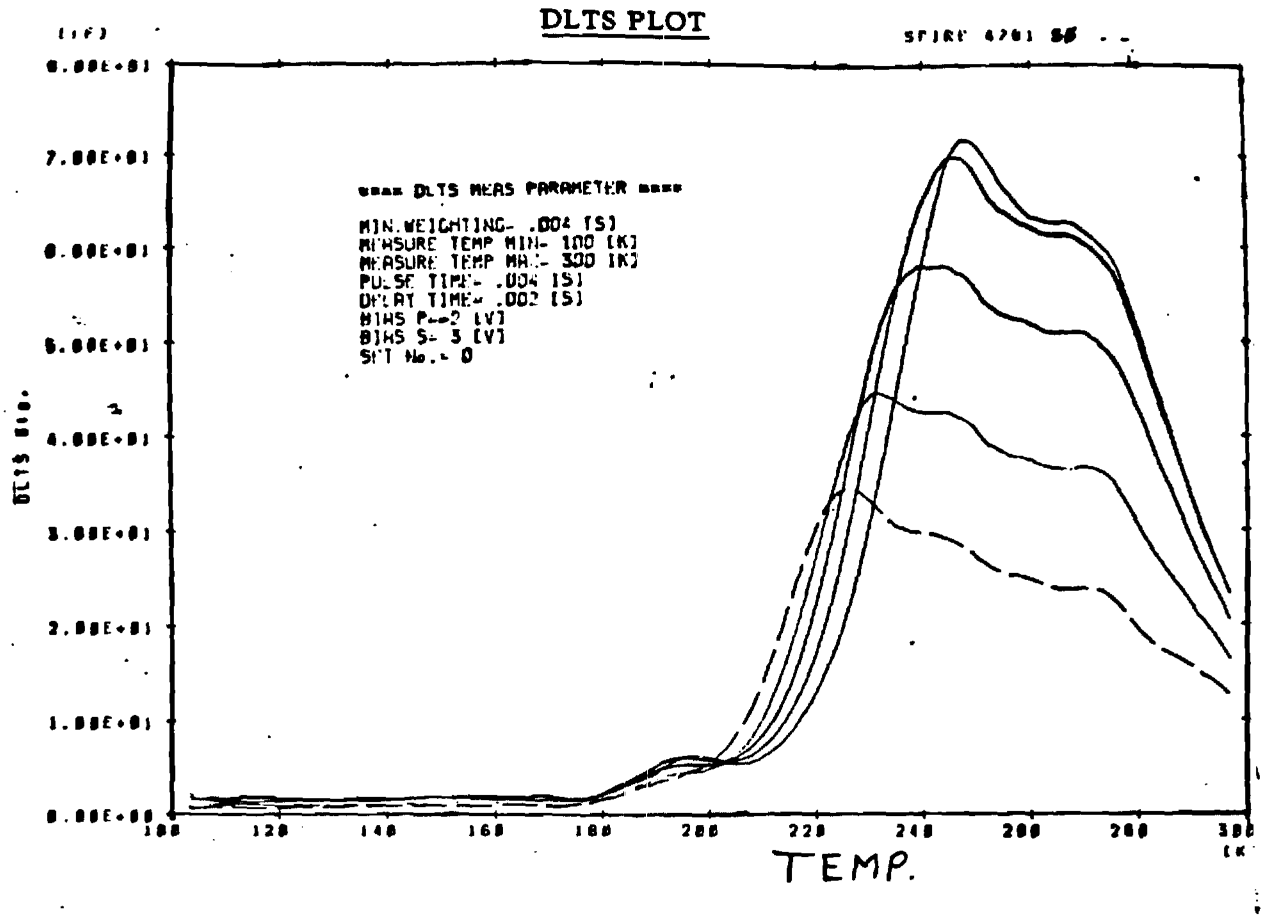
Figure 31 shows the output of our automated DLTS system for the sample So, which was ion implanted and then etched with KOH to remove the implanted region. A Ti-Ag Schottky barrier was made for the DLTS measurements. This sample, which was supposed to be a representative of the as-grown material because the implanted region was removed, showed two large deep levels at E_V + 0.41 eV and E_V + 0.86 eV with trap densities

TABLE 14

Diffusion Length and Description of SPIRE Samples for DLTS Measurements

Sample ID	Diffusion Length (μm)	Sample Description
S_1	20	FA W/o Cl + II + LA
S_2	150	Cl + II + LA
S_3	120	Cl + FA + II + LA
S_4	60	Cl + II + FA + Etched + Cl + II + LA
S_0	--	II + KOH Etched

NOTE: FA: Furnace annealed
Cl: Cleaned
II: Ion implanted
LA: Laser annealed



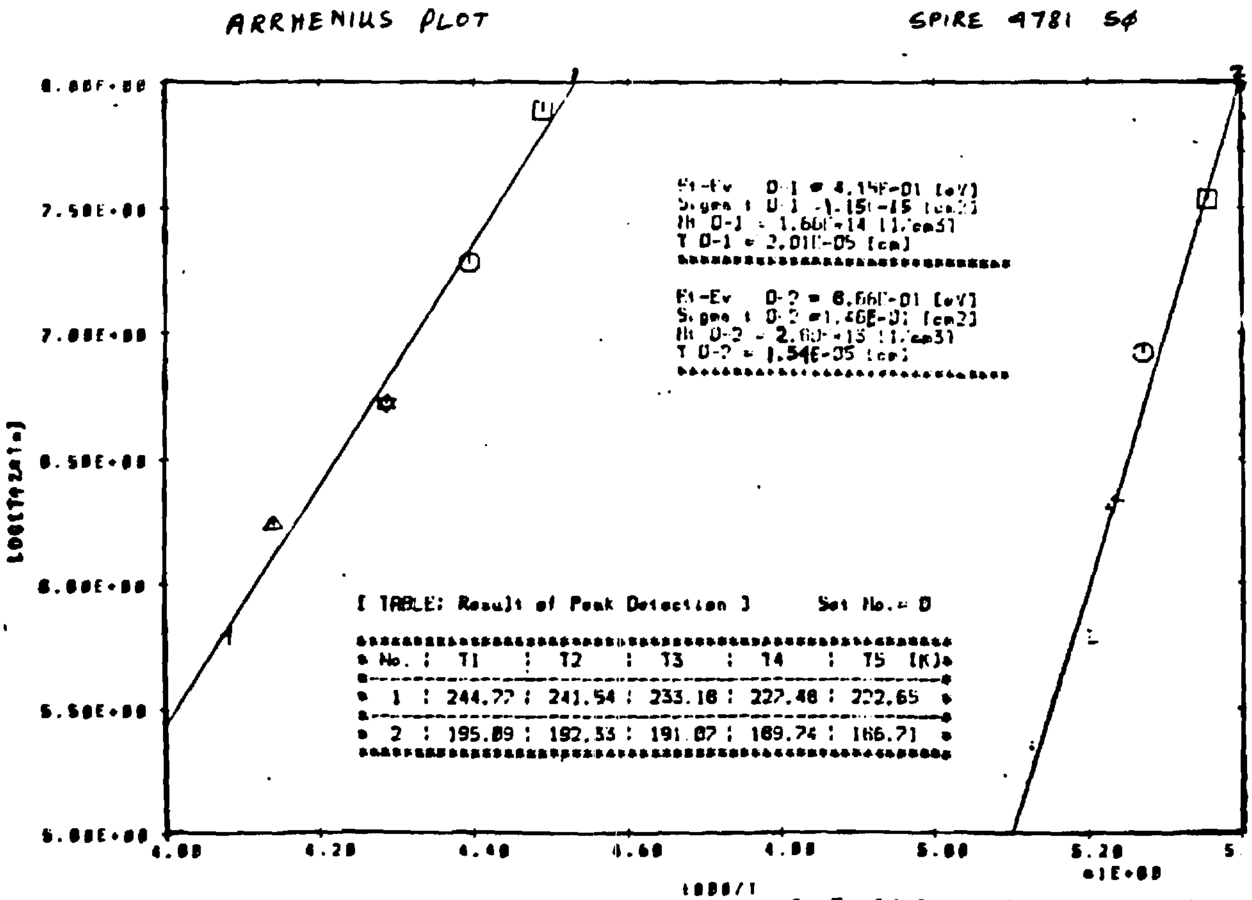


Figure 31: DLTS Spectra and Arrhenius plot for sample 5 which was ion implanted then Koh etched.

of 1.66 x 10^{14} Cm^{-3} and 2.8 x 10^{13} Cm^{-3}, respectively. We believe that ion-implantation + KOH removal introduced these levels and that they are not present in the starting material.

Comparison of the DLTS spectra for samples S1 and S2 (Figure 32) show that sample S2 has no peaks but S1 has two peaks. S1 was annealed without any preclean followed by ion implantation and laser anneal while S2 was first cleaned properly then ion implanted and laser annealed. We conclude from the DLTS spectra that the furnace anneal without any cleaning is responsible for introducing two deep levels, L_1 and L_2, which in turn reduce the diffusion length to 20 microns.

Sample S3 which was cleaned + furnace annealed + ion implanted + laser annealed showed only one level L_2 and not the L_1. A comparison of samples S_3 and S_1 suggest that level L_1 is due to omitting the precleaning step prior to furnace anneal. Since the deep level L_2 is common to both samples S1 and S3, the data indicate that level L_1 is a lifetime killer because of which diffusion length in the sample S1 is only 20 microns compared to 120 microns in sample S3.

A comparison of DLTS spectra for samples S2 and S3 suggests that the level L2 observed in sample S2 is due to the furnace contamination because S3, which never saw the furnace anneal, showed no deep levels. Thus level L2 is also a lifetime killer and its presence decreases the diffusion length in sample S3 to 120 microns compared to 150 microns in S2.

Sample S4 was cleaned + ion implanted + furnace annealed + etched and then cleaned + ion implanted + laser annealed. Compared to sample S3 this sample had an additional implant but its diffusion length is only 60 microns. Both S3 and S4 showed the deep level L2 with similar trap density. At this point, based on surface DLTS measurements, it is difficult to explain why S3 has a diffusion length of 120 microns

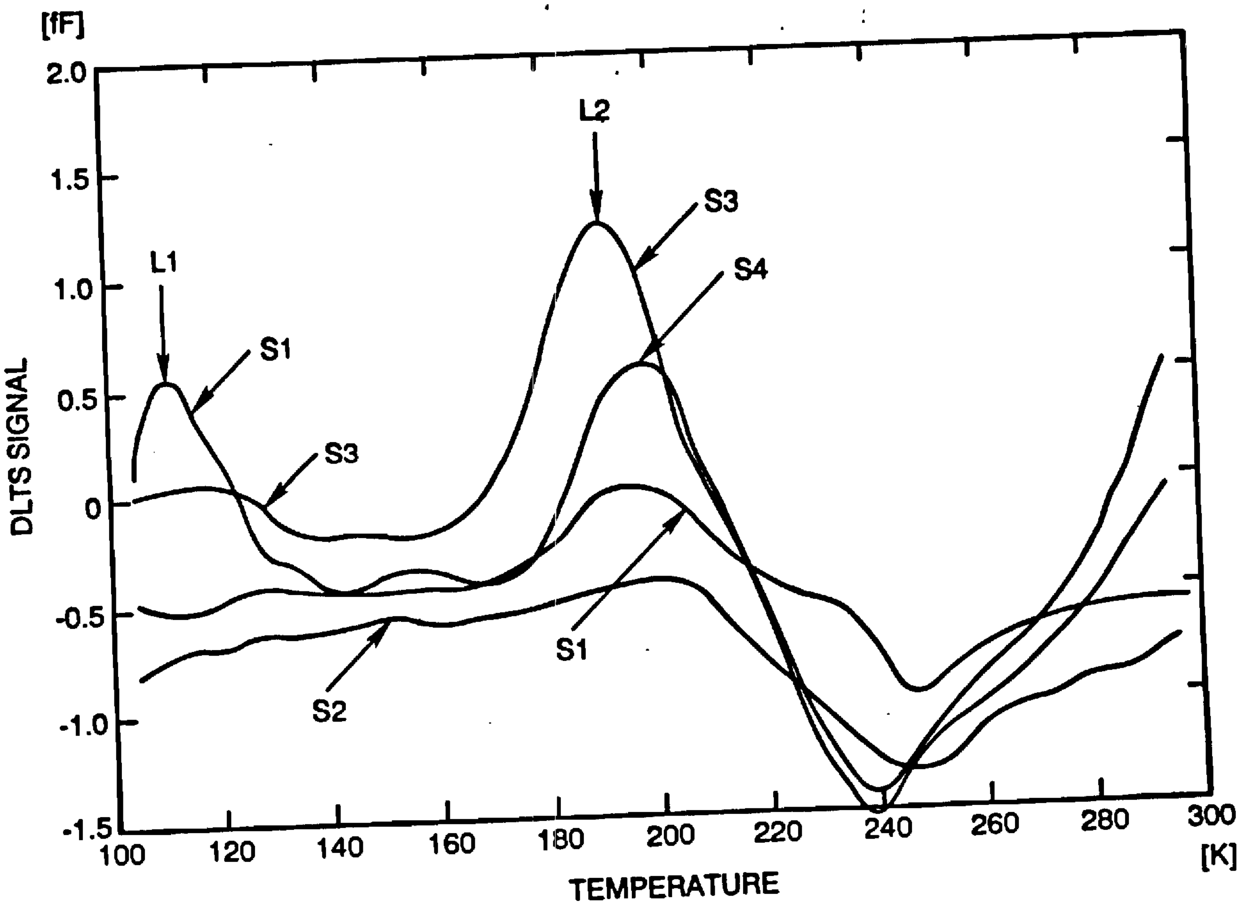


Figure 32: DLTS spectra for samples S_1, S_2, S_3 and S_4 as shown in Table 14.

while S4 has a diffusion length of 60 microns.

The above preliminary DLTS measurements on Spire processed material suggest that a combination of improper cleaning and furnace contamination is responsible for reducing the diffusion length in the Spire cells to less than 150 microns. However, implanted and laser annealed (not furnace annealed) cells appear clean with no detectable deep levels and a diffusion length of $\geq$ 150 microns. It should be recognized that our DLTS detection limit for these 0.3ohm-cm p-type float zone silicon samples is about 10^{13} cm^{-3}.

2.2 (b) DLTS and PCD Lifetime Measurements on Ion Implanted High Resisitivity Samples from Spire

In the previous experiment 0.3 ohm-cm silicon was used which puts the DLTS detection limit to $\sim 10^{13}$ cm^{-3}. Therefore, in this second experiment we decided to investigate 100 ohm-cm material along with 0.1-0.3 ohm-cm material. A total of 11 samples were received from Spire Corporation. Of these, 5 samples were p-type with resistivity of 0.1-0.3 ohm-cm and the other 6 were n-type with resistivity of 100 ohm-cm. We were unable to make good Schottky barriers on low resistivity silicon and therefore DLTS measurements could not be performed. This is due to the fact that such low resistivity silicon tends to give ohmic contact or very leaky junction which prevents successful DLTS measurements.

Good quality Schottky barriers were fabricated on 100 ohm-cm n-type samples by Au evaporation. The DLTS spectra for all six n-type samples is shown in Figure 33. To see a direct correlation between the lifetime and DLTS peaks, we performed lifetime measurements on bare silicon

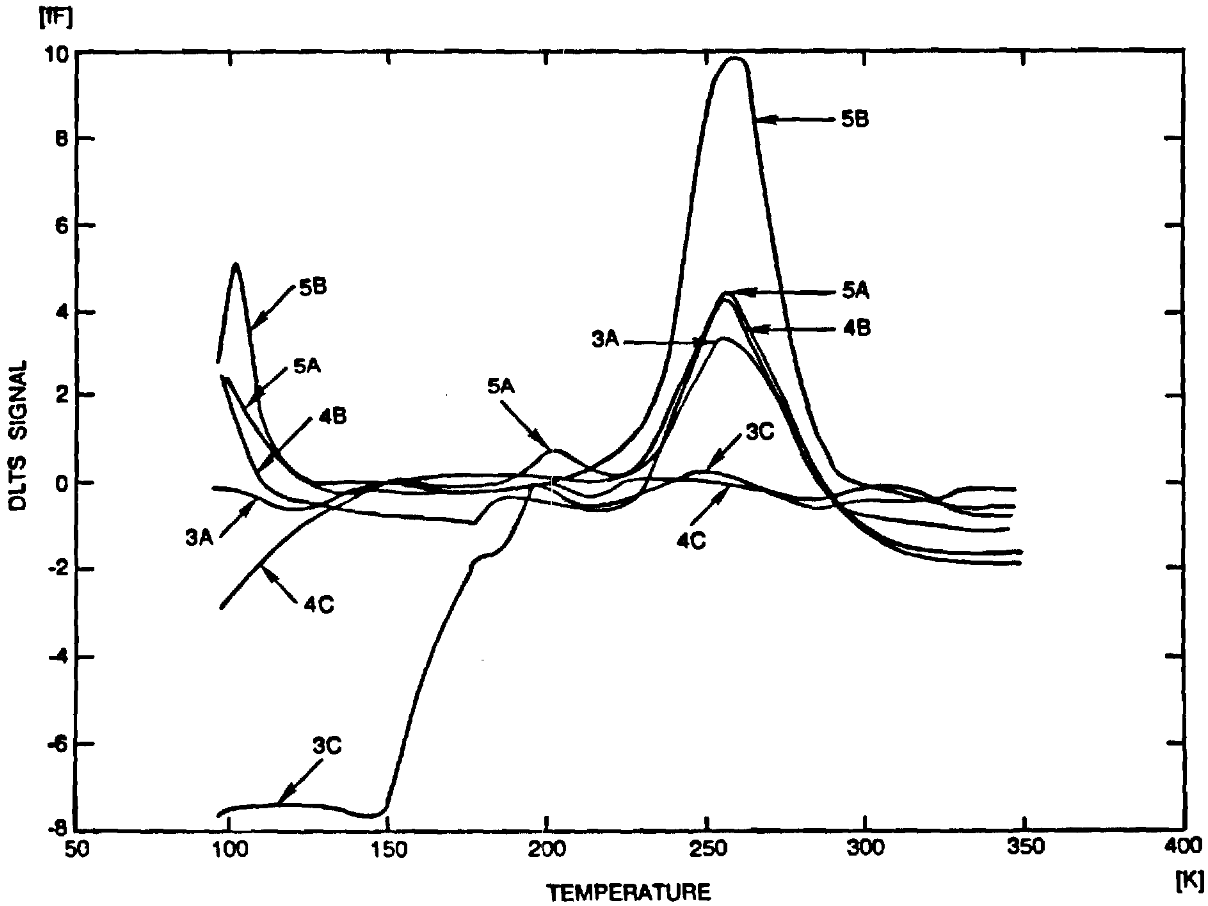


Figure 33: DLTS spectra for six high resistivity n-type samples as shown in Table 15.

pieces by a PCD technique. In this technique silicon wafer is immersed in concentrated HF during the photoconductive decay process. Concentrated HF is able to passivate the silicon surface to a recombination velocity of less than 20 cm/sec so the photoconductive process is primarily dictated by the bulk recombination. PCD lifetimes are tabulated in Table 15. This technique cannot measure lifetimes below 20μs. This limit is imposed by the rise and fall time of the Strobe lamp being used in the measurement to exite the carriers.

Samples 3C and 4C were neither implanted nor annealed and both of these showed no peaks in the DLTS spectra. This is consistent with the high lifetime (0.2) ms in both the as-grown samples.

Samples 3A and 4B were not implanted but 3A was annealed in nitrogen and 4B in oxygen. The DLTS spectra of both samples (Figure 33 showed an energy level at E_c-E_t ~0.19 eV, suggesting that Spire annealing process created a defect level in silicon. Also from the relative height of the DLTS peaks it can be concluded that annealing in oxygen ambient results in higher trap density compared to the nitrogen ambient.

Samples 5A and 5B were implanted. 5A was annealed in nitrogen and 5B in oxygen. DLTS spectra showed higher trap density in these samples compared to samples 3A and 4B. This indicates that implantation process, followed by annealing, promotes further growth of the lifetime limiting trap. The DLTS spectra for these two samples again reveals that oxygen annealing is worse than nitrogen annealing. No lifetime data could be obtained for samples 5A and 5B because of the very low lifetimes due to the large trap density.

It appears that implantation prior to annealing does not create additional trap levels but it does enhance the annealing-induced trap density. Oxygen ambient is worse than nitrogen with regard to trap density. No lifetime data could be obtained on samples 5A and 5B simply

TABLE 15

DLTS and PCD Lifetime Results on 100 ohm-cm N-Type Silicon

Sample ID	Implanted	Annealing Condition	Lifetime (τ) (ms)	DLTS Signal
3A	No	Nitrogen	NA	Single Peak $E_c - E_t \sim 0.19$ eV
3C	No	None	0.2	No Peaks
4B	No	Oxygen	0.08	Single Peak $E_c - E_t \sim 0.19$ eV
4C	No	None	0.2	No Peaks
5A	Yes	Nitrogen	<.02	Single Peak $E_c - E_t \sim 0.19$ eV
5B	Yes	Oxygen	<.02	Single Peak $E_c - E_t \sim 0.19$ eV

because lifetime values went below 20 micro-seconds. This is consistent with the increased DLTS trap density. The fact, that peak height in DLTS spectra is inversely related to the lifetime values for all the samples, strongly suggests that Ec -0.19 eV trap detected by DLTS is responsible in degrading the lifetimes in the Spire cells. Although the origin of this trap is the annealing process but implantation aggravates the problem. At this time we do not have a good idea of the nature of this defect. Further experiments are needed to identify the contaminant or the defect.

2.3 Characterization and Modelling of GaAs Heteroface Solar Cells

MOCVD grown cells were obtained from Spire Corporation and were subjected to DLTS, I-V-T, spectral response, light and dark I-V measurements, followed by PC-1D and surface recombination velocity models to provide guidelines for better cells[6]. The cell structure consisted of 0.5μm p-type emitter 2×10^{18} cm^{-3} on a 2μm n-type base (2×10^{17} cm^{-3}) with a 2μm p+ buffer layer and a p+ AlGaAs passivating window layer. This particular cell had a measured efficiency of 21.2%.

Figure 34 shows a comparison of the measured and calculated spectral response using a front surface recombination velocity of 1.25×10^{15} cm/s and a net base lifetime of 8 ns. The SRH lifetime was calculated from this by including band-to-band and Auger recombination contributions to the overall lifetime. Subsequently, an emitter lifetime of 2 ns and a buffer lifetime of 5.5 ns was calculated by accounting for the variation of the radiative recombination coefficient with doping level.

In order to test the values of S and τ_b, we used the effective recombination velocity model developed by Davis and Rohatgi[7] which

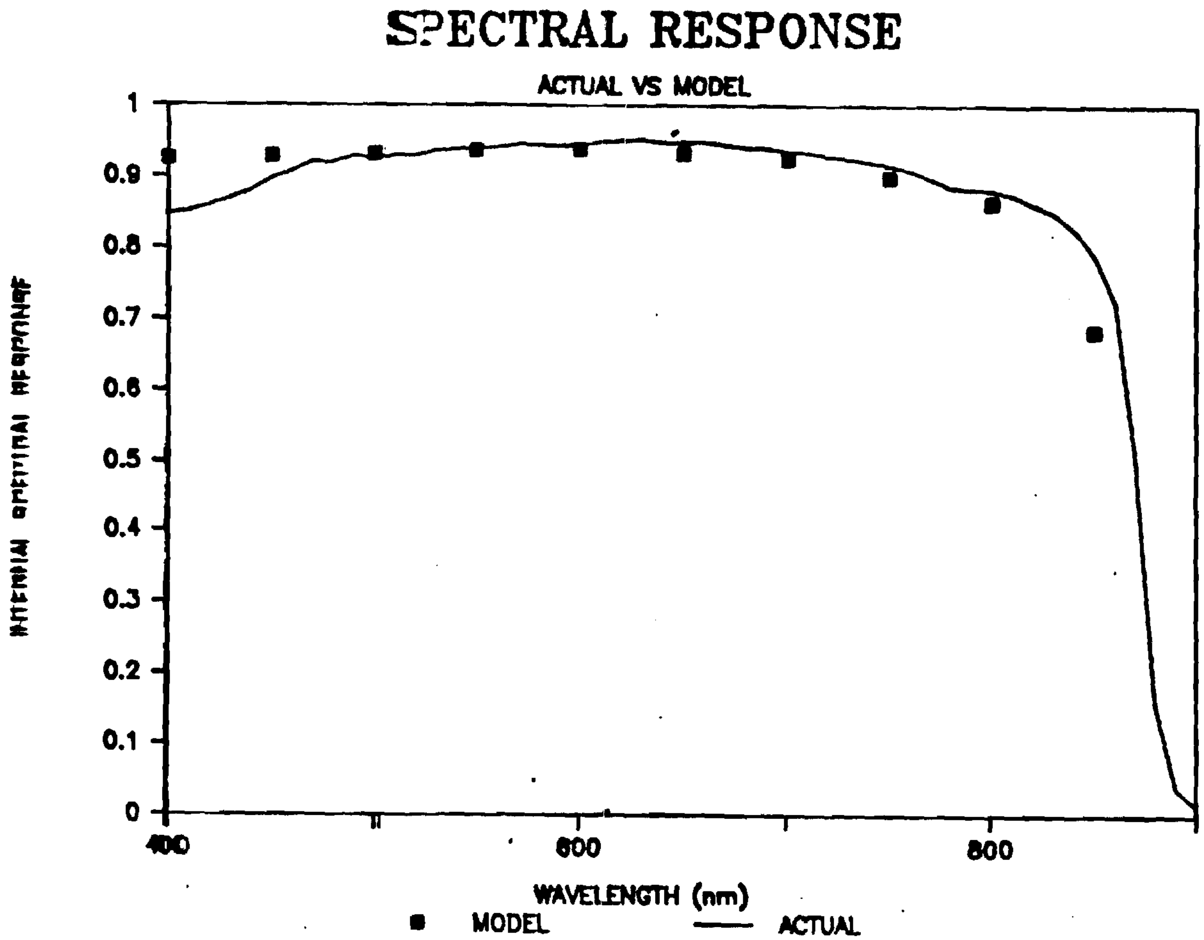


Figure 34: Comparison of modeled (solid squares) and actual (line) spectral response for the cell.

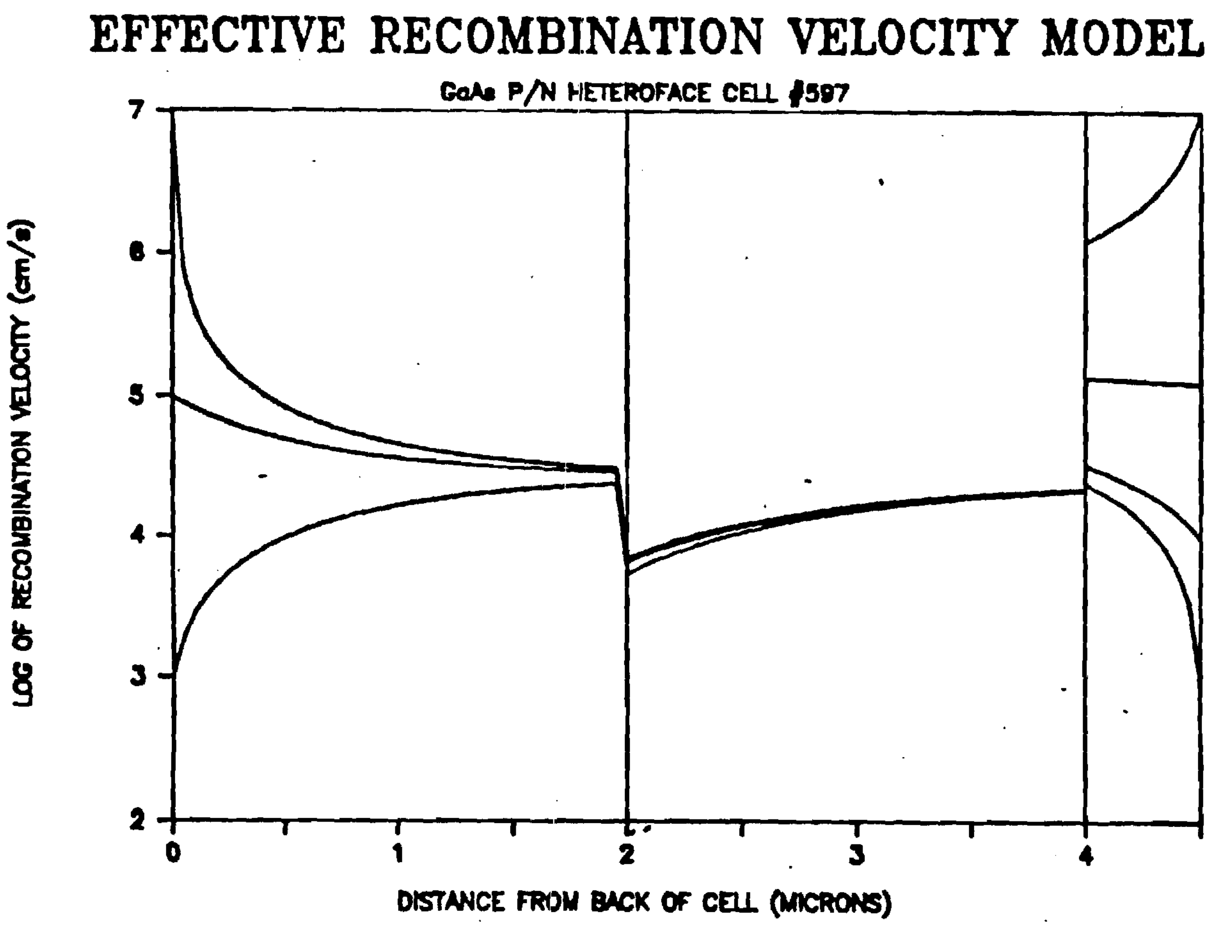


Figure 35: Effective recombination velocity plot for various values of FSRV and BSRV.

TABLE 16

Comparison of Measured and Modeled Cell Data with Design Guidelines for Improved Efficiency

ID	FSRV (cm/s)	BSRV (cm/s)	N_A (cm^{-3})	N_D (cm^{-3})	τ_B (sec)	J_{sc} (mA/cm^2)	V_{oc} (V)	EFF (%)
Actual			$2x10^{18}$	$2x10^{17}$		24.5	1.013	21.2
Match	$1.25x10^{5}$	$1.0X10^{6}$	$2X10^{18}$	$2x10^{17}$	$8x10^{-9}$	24.56	1.009	21.39
	1.0 x 104	$1.0x10^{4}$	$2x10^{18}$	$2x10^{17}$	$8x10^{-9}$	26.71	1.017	23.13
	$1.0x10^{4}$	$1.0x10^{4}$	$2x10^{18}$	$2x10^{17}$	$15x10^{-9}$	27.108	1.032	24.17

Conclusions

We have performed model calculations to design greater than 20% efficient cells using low resistivity silicon (0.1 - 0.3 ohm-cm) and conventional n+-p-p+ cell structure with oxide passivation and textured surface. Using identical cell structure but higher resistivity (15-200 ohm-cm) and high lifetime (1-10 ms) silicon, cell designs have been developed for achieving ~25% efficient cells. Necessary modifications have been made to account for the textured surface effect in PC-1D model. None of the simulations gave clear cut superiority of one resistivity over the other. Yet, all the efficiency calculations using n^{+}-p-p^{+} structures indicated optimum thickness in the range of 150-300 microns, regardless of the lifetime value in the range of 1-10 ms.

A comparison between PC-1D, SCAP-1D, SPCOLAY and SRV models have been made using similar inputs. Most models agree within 0.5% absolute efficiency, with slight differences in the predicted values of Jsc and Voc.

DLTS analysis on ion implanted and/or annealed samples indicated that Spire's annealing process by itself introduces a deep level at Ec-0.19 eV which is responsible for the low diffusion length in Spire cells. Ion implantation followed by anneal does not introduce any new traps, however, the density of the annealing-induced trap is increased. Carrier lifetime was found to be inversely proportional to this trap density, strongly suggesting that Ec-0.19 eV is the lifetime killer in the Spire cells. This defect should be eliminated by improving or cleaning the annealing process before very high efficiency cells from high lifetime silicon can be processed at Spire. At this time the identity of this defect is not known.

A detailed analysis of MOCVD grown 21.5% efficient GaAs cell was performed by a combination of measurements and modelling. A methodology was developed to assess important parameters like minority carrier lifetimes in the emitter and base along with the recombination velocity at the AlGaAs/GaAs interface. This was done by matching the measured and calculated values of spectral response, reverse saturation current, Voc, Jsc, and cell efficiency with help of PC-1D and surface recombination velocity models. It was established that the 21.5% efficient cell investigated in this work, was partly base and partly emitter limited. Model calculations also suggested that its efficiency can be improved to 24.5% by improving base lifetime from 8ns to 15 ns and reducing the AlGaAs/GaAs interface recombination velocity from 1.25×10^{15} to 1×10^{14} cm/sec.

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Acknowledgements

The authors would like to thank Mark Spitzer, Chris Keaveny and Steve Tobin of Spire Corporation for the helpful discussions and sampels, Ted Ciszek of SERI for his inputs and discussions, Paul Basore of Sandia Lab for the guidance in using PC-1D program, M. Wolf of the University of Pennsylvania for SPCOLAY model and Kay Meeks for typing the manuscript.